ELECTRIC CABLES

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THEIR DESIGN, MANUFACTURE AND USE

A Series of Lectures Delivered in the Moore School
of Electrical Engineering of the University
of Pennsylvania, 1923–24

BY

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PREFACE

In the fall of 1923, the Moore School of Electrical Engineering of the University of Pennsylvania inaugurated the practice of supplementing the regular courses of instruction by lectures to the Senior Class, to be given by practicing engineers not connected with the University.

The author was the first to give such a course, which was planned to comprise fifteen lectures. Very little time was available for the preparation of the lectures, which were, therefore, of an informal character. The faculty of the University, however, requested that notes of the lectures be prepared for distribution in mimeographed form.

The interest evinced in these notes by outside engineers suggested the desirability of putting them in book form, so as to make them available to a larger number of engineers and students. This has been done in the present volume.

The notes are considerably more condensed than the actual lectures, which occupied about an hour and a half each. The number of illustrations has also been greatly reduced, as many of the slides exhibited had no permanent value. The division of material into chapters differs somewhat from its division into lectures.

As the principles of electrical engineering are taught by Dean Pender and his able teaching staff, it would have been superfluous to have entered into the mathematical derivation of formulas. Hence, while the lectures abounded in formulas, standard theory and mathematical arguments were avoided.

The lack of an up-to-date book on Wires and Cables is the author's excuse for presenting one of this informal character.

William A. Del Mar.

Greenwich, Conn.

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ELECTRIC CABLES

CHAPTER I

THE CABLE USER'S PROBLEM

INTRODUCTION

The art of electrical engineering depends upon the use of wires or cables to direct the flow of energy from its source to a point of utilization. Hence, while different machines and apparatus are required for the generation and utilization of electrical energy for illumination, traction, electrochemical processes, telephony, telegraphy, etc., wires and cables are essential to all these arts, and, considering electrical plants in the aggregate, the value of the conductors greatly exceeds that of any other single item. It is, therefore, obvious that the proper design and operation of the conductor system are matters of great public and commercial importance, to which a high grade of engineering talent may be profitably devoted.

The first consideration is safety to human life; that is, cable systems should be so safe that no ordinary and probable combination of circumstances will cause a condition of unsafety. Next to safety to human life is safety to property, a consideration intimately connected with the preceding one. After safety, the next most important consideration is adequacy, by which is meant that the conductors and their accessories must be of the correct dimensions and quality to perform their required service. After adequacy, and intimately connected with it, comes reliability. The use of electric power has become such an important and integral part of present-day life that interruptions of the supply have most serious effects. The failure of light to a district means not only inconvenience, but often great hardships. The failure of power to a railway means interruption of service, with all the attendant inconvenience and hardships. The failure of power to an industrial plant means throwing

men out of work and decreasing the plant's production, with all the evil consequences which follow. The attention of operating men has been devoted increasingly to obtaining more reliable cables, and every year sees more stringent specifications designed to secure this object. After reliability comes sightliness. In the case of outdoor wires, the community in which the conductors are to be erected obviously has the right to balance the loss of sightliness against the gain in utility or economy due to their presence. This has led, in many places, to the requirement that conductors be buried underground instead of carried aerially.

When safety, adequacy, reliability and sightliness have been given due consideration, the matter of expense has to be considered. The total expense is composed of the following items, which may be expressed as annual charges:

1. Interest on first cost of conductors and accessories.
2. Amortization of debt incurred by their purchase.
3. Depreciation annuity or other charge to permit their replacement when no longer serviceable.
4. Cost of energy loss in conductors and dielectric.
5. Maintenance and repair charges.
6. Increase or decrease of insurance or risks due to type and construction of conductors and their accessories.

Conductors and their accessories should be designed so that, with due consideration of safety, adequacy and sightliness, the total annual cost is a minimum. This statement is the sum and substance of the engineering of wires and cables.

To the solution of this problem must be brought a knowledge of electrical principles, properties of materials, operating conditions, limitations of manufacture, costs and, last but not least, human nature.

KINDS OF INSULATION EMPLOYED

Underground paper cables to the value of about $25,000,000 are installed every year in the United States. The aggregate value of these cables installed since 1890 is not far short of $300,000,000. The prospect of their increased use in the future is linked with the probable increase in the nation's population and wealth. Wherever cities are growing, aerial wires are being taken down and replaced by cables; wherever industrial loads are

outgrowing the open-wire aerial distribution systems, underground cables are coming into use.

Every lighting or railway company in cities of over 100,000 population and every large industrial concern uses cables for transmission. It is, therefore, necessary for most electrical engineers to be familiar with their construction, properties and use.

Impregnated-paper-insulated, lead-covered cables are generally used for transmission and outdoor distribution. The first reason for this is that impregnated-paper cables may be loaded until their temperatures reach the limits imposed by expansion and contraction, which is usually regarded as being between 60 and 85° C. In other words, the component materials of impregnated-paper cables are so stable chemically and electrically that consideration of their stability does not affect the maximum permissible operating temperature. Rubber, on the other hand, oxidizes so rapidly at 70° C. that it deteriorates as much in 96 hr. at that temperature as it does in two years at ordinary atmospheric temperatures. This action occurs when rubber is exposed to the air; if protected by a lead sheath, only the air between the copper strands will come into play, and oxidation will not only be less rapid but will be confined to the inner surface. Lead-covered, rubber-insulated cables, however, are very expensive.

Large low-tension feeders for underground service therefore almost invariably are insulated with impregnated paper. The qualifying word "underground" is used because in buildings where feeders are short, and often have vertical runs, either rubber or varnished cambric is superior. Varnished cambric insulation is inferior to impregnated paper in most of its characteristics and is more expensive.

At high voltages, the inevitable air pockets in rubber insulation, especially those between it and the copper or lead, become ionized, and their oxygen converted into ozone, which rapidly cracks open the rubber. If the rubber is not lead-sheathed, air ionization may occur at the outer surface, with the formation of the same characteristic cracks. Furthermore, the high power factor and excessively high charging current of both varnished cambric and rubber insulation lower the carrying capacity so much at high voltages that such cables have a much lower kilowatt-carrying capacity at high than at low voltages.

CHAPTER II

HISTORICAL NOTES

Wire was originally made by beating metal into plates, which were then cut into strips and rounded by beating.

The art of making wire by drawing metal through dies appears to have been invented in the fourteenth century. It did not come into use in England before the second half of the seventeenth century.

Wires were gaged by numbers early in the eighteenth century. The earliest gages were based upon the successive sizes which it was considered good practice to draw; thus, No. 1 was the first step after the original rod, and each of the succeeding numbers corresponded with the number of dies which it passed through, so that No. 10, for instance, passed through ten dies.

The first attempt to adopt a geometrical system was made by Browne and Sharpe in 1855. They established a regular geometrical progression of 39 steps between the English sizes 4/0 (460 mils) and 36 (5 mils). The ratio of this progression is:

$$\sqrt[39]{\frac{460}{5}} = 1.122932.$$

Hence, each diameter is multiplied by this figure to give the next larger size. This is now known as the "American wire gage" (see Appendix II).

In the early eighties, when Edison introduced electric light systems, some method of rating cables larger than 4/0 was found necessary, and he introduced the circular mil gage, according to which the cross-section of a conductor is stated in terms of a unit of area equal to that of a circle 1 mil in diameter. The area of any cylindrical conductor in circular mils is equal to the square of its diameter in mils. The area of stranded conductors is based upon the assumption that all the strands are laid out straight and their areas added together.

Electric cables were first used for explosive mines, and telegraphs.

The first electric mine was invented in about 1812 by a Russian named Schilling, who fired the mine by a rubber-insulated cable under the Neva. It is also reported that the same inventor developed a telegraph, for which he installed a cable in the river Isar near Munich.

The earliest record of the employment of a permanent insulated wire successfully was in connection with experiments conducted in 1816 by Francis Ronalds at Hammersmith, England. This inventor developed a crude telegraph system, and included in his circuit about 150 m. of underground wire. This wire was bare and passed through heavy glass tubes, the ends of which were butted and joined by sleeves, which were sealed with wax. These glass tubes were placed in pump logs, that is to say, wooden pipes. Ronalds developed underground systems to a surprising extent, predicting the necessity for providing for ready access to the wire and for the localization of faults. With this in view, he developed junction boxes at regular intervals.

The next important step of which record was found related to experiments by Colonel Pasley of Chatham, England, in 1838. His insulation consisted of strands of tarred rubber and pitched yarn.

About the same time other inventors installed insulated cables in wooden troughs.

In 1838 the line between Paddington and Slough (London) was constructed of cotton-covered wire impregnated with rosin compound and enclosed in iron pipes.

About 1840 Samuel B. Morse laid underground about 5 mi. of wire covered with cotton soaked in shellac solution and drawn into lead tubes. This experiment was a failure.

In the year 1840 Jacobi of St. Petersburg repeated the experiment, using rosin to fill the air spaces in the lead tube. His attempt was successful. He also constructed an underground telegraph line in 1840, employing insulated cable drawn into pipes.

In 1841 Morse designed a cable insulated with a covering of rubber, hemp, tar and pitch for use in a submarine telegraph line across New York Harbor, and in 1842 it was placed in successful operation.

Vulcanization of rubber was placed upon a practical basis about 1844 as the result of experiments by Ludensdorf, Haywood, Goodyear, Hancock and others. Gutta percha was also used in cables made in Germany in 1846.

In 1845 Wheatstone and Cook patented a cable consisting of copper wires covered with cotton, united into a group and the whole enclosed in a lead tube.

During the years 1846 to 1849 considerable quantities of gutta-percha-insulated cables were made and laid as underground lines in Germany at the suggestion of Siemens Brothers.

In 1847 Werner Siemens invented a machine for applying seamless gutta percha to wire. Previously, he had covered the wire with strips of gutta percha, but much trouble was experienced from moisture penetrating at the seams where the strips met. The manufacture of gutta-percha-insulated cables was started in England in 1849 by the Gutta Percha Company. They made the first cable to be laid across the English Channel in 1850.

The second Anglo-Continental line, built in 1851, was provided with a complete armor of iron wires.

Steel-tape armor was the subject of a patent taken out in 1852 by E. B. and C. B. Bright.

The first Atlantic cable, which was laid shortly before the Civil War, was a failure, due to the excessively high-voltage tests which were made upon it. Therefore, during the Civil War the United States was not in telegraphic communication with Europe.

The second Atlantic cable was laid in 1866. It was composed of stranded copper conductors insulated with gutta percha covered with tar and hemp, and protected by iron-wire armor.

In 1879 the invention of the carbon filament incandescent lamp and Edison's pioneer work in developing the details of the electric lighting system led to the first demand for cables for power distribution.

The first distribution system, which was laid in New York City, consisted of copper rods wrapped in impregnated cotton or jute and placed in iron pipes 20 ft. long. This type of insulation was at first entirely unsatisfactory, but it was improved by saturating the conductor, jute, the pipe and the assembling materials with tar compound. Some of the later Edison pipes are said to be in operation at the present time.

François Borel of Switzerland invented a practical lead press for applying a lead sheath in 1879, and in 1884 made 2,000-volt cables for Vienna.

During the early eighties, Brixey, Habirshaw and other experimenters produced vulcanized-rubber insulation and began to manufacture it on a commercial scale.

About 1890 Callender of England began to make impregnated-paper cables and two years later they were made in America by the Norwich Wire Company and its successor, the National Conduit & Cable Company. Other companies soon followed.

In 1902 the General Electric Company began to make varnished-cambric cables and was soon followed by other companies. In about 1910 varnished cambric was improved by the addition of black asphaltic material, which had the effect of improving the quality of the insulation at high temperatures.

The original paper cables were impregnated with a mixture of rosin oil, rosin, castor oil and other substances, but about 1918 this type of compound was replaced by one consisting basically of petrolatum.

Considering the recent development of the art of electrical engineering, the difficulty of obtaining authentic historical information about cables is very surprising. The author would appreciate any assistance which readers may be able to give in order to make a more complete story for another edition.

CHAPTER III

MATERIALS USED IN WIRES AND CABLES

IMPREGNATED-PAPER CABLES

Impregnated-paper cables are made of very few materials—copper, paper, impregnating compound and lead. Sometimes, but not often, the lead is hardened with tin, antimony or magnesium. The impregnating compound is either petrolatum, or a mixture of that oil with other oils or resin. Formerly, a mixture of rosin oil and resin was used for impregnating, but it was abandoned because it gave high dielectric loss, low dielectric strength at high temperatures and excessive stiffness at low temperatures. It is also unstable chemically at high temperatures. Many European manufacturers use a mixture of cylinder oil and resin, in about equal proportions.

Petrolatum is a heavy mineral oil, which is a jelly at ordinary temperatures and becomes a liquid at about 55° C. All petrolatums are derived from paraffin-base petroleum; some grades are made from oil-well pipe scrapings and others from the residue of the steam "cracking" process used in breaking crude oil into the lighter varieties.

The present tendency is to omit the resin from compounds and to use either pure petroleum of a special grade, or a mixture of petrolatum and other oils. Transformer oil, resin oil and castor oil are the principal modifiers now in use.

When tested between 1-in. discs, $\frac{1}{10}$ in. apart, petrolatum breaks down at a tension between 25 and 35 kv. The relation between this tension and that obtained with other electrodes is given in Table I, which was prepared by a committee of the American Society for Testing Materials.[1]

[1] The true dielectric strength, *i.e.*, the limiting stress at the energy distance, has not been accurately determined in relation to these tests, but it is believed that, expressed in kilovolts per centimeter, it is approximately equal numerically to the breakdown tension in kilovolts derived from the test with 1-in. discs $\frac{1}{10}$ in. apart.

The resistivity of commercial grades of petrolatum is liable to vary from 0.1 × 10^{12} to 40 × 10^{12} ohm-cm., when tested in the cell designed by C. F. Hanson and described in the *Transactions of the A.I.E.E.*, 1922, page 569.

The paper used for American cables is pure manila-rope paper, made from selected used ropes. Europeans prefer either a mixture of manila and wood fiber or pure wood fiber. The usual thicknesses in American practice are from 2½ to 8 mils, the commonest sizes being 5, 6 and 8 mils.

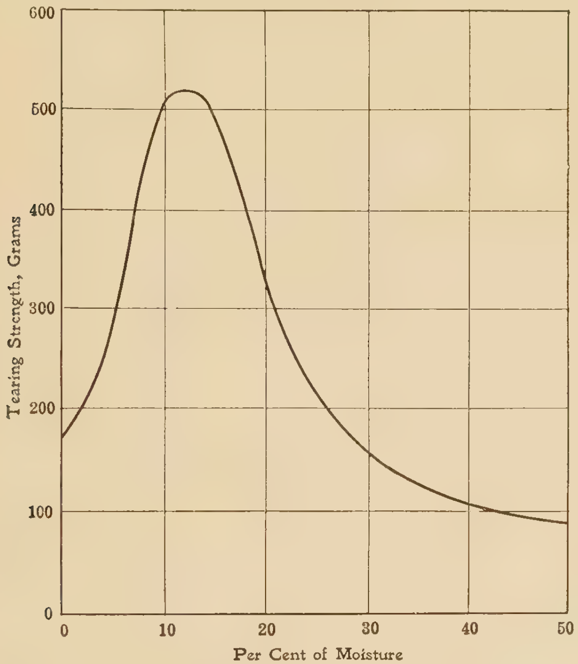

FIG. 1.—Relation between tearing strength and humidity of manila rope paper.

Manila-rope paper is made by macerating old manila rope, cleaning the resultant fibers and depositing the pulp on gauze cylinders, which retain the fibers and let the water pass through. A continuous sheet of felted fibers is drawn from the cylinders, of which two are used, and the sheets are united by pressure and heat on a series of steel calendering rollers similar to those of a Fourdrinier machine.

The finished paper usually contains from 4 to 8 per cent of moisture, which lends it mechanical strength. The relation

between tearing strengths and moisture content is shown by the curve in Fig. 1. It will be noted that both very dry and very wet paper have low tearing strength as measured on an Elmendorf tester, and that a maximum is attained with about 13 per cent of moisture.

After impregnation, the tearing strength of 5-mil paper is about the same as when thoroughly desiccated. This is about 60 to 70 per cent of its normal air-dry strength.

The tensile strength of paper is not a good indication of its condition, as it may be quite brittle and yet show considerable tensile strength. The best test is undoubtedly that of folding endurance, but it is not generally used, because no testing apparatus has yet been standardized.[1]

The compactness of the fibers in paper is of great importance from the point of view of impregnation, dielectric strength and constancy of power factor.

The scientific selection and control of raw materials is of even greater importance in impregnated-paper cable manufacture than the control of manufacturing processes. That is to say, greater latitude is allowable in processes than in the essential properties of the paper and oil. Indeed, success in manufacture is largely a matter of preserving the essential characteristic of the original pure materials.

TABLE I

Shape	Type of electrode			Relative breakdown voltage
	Diameter, inches	Distance apart, inches	Position of axis	
Discs	1	0.10	Horizontal	1.00
Discs	½	0.20	Horizontal	1.82
Spheres	½	0.15	Vertical	2.00

[1] An apparatus for this purpose has recently been developed by Prof. Bush of the Massachusetts Institute of Technology—for the Cable Research Committee of the N.E.L.A. and A.I.E.E.—which represents the latest development in apparatus for this type. It is made by Tinius Olsen.

RUBBER-INSULATED CABLES

Rubber insulation is made of the following four elements:

1. New rubber, which is the principal insulating element.

2. Sulphur and accelerators, which vulcanize the rubber and render it comparatively immune from oxidation. The most common accelerator is litharge. Red lead, which is listed below as a filler, is a weak accelerator.

3. Fillers, which harden the rubber, giving it the mechanical qualities necessary for practical handling. The most usual fillers are zinc oxide, red lead, talc and whiting.

4. Softeners, which give the compound the requisite fluency to manufacture readily without injury. They also enable the insulation to stretch without undue increase of porosity. The most usual softeners are paraffin wax, oxidized oils, asphaltic materials and reclaimed rubber, although the latter is usually classified as an adulterant or cheapener.

Practically all rubber insulation is made of hevea rubber, which is the product of a tree native to equatorial South America but now grown on plantations in many tropical countries.

Hevea rubber is distinguished from other types by the following characteristics:

The extract derived from digesting the rubber in acetone, when saponified with an alcoholic solution of potash, is between certain maximum and minimum limits, and the unsaponified resins in the extract never exceed a certain maximum.

Rubber which falls within these chemical limits is necessarily hevea rubber, but the physical properties vary widely without corresponding chemical differences. The reason for this is that rubber is not an homogeneous substance but an aggregation of globules of a material called "caoutchouc" cemented together by a resinous matrix. The physical properties of the caoutchouc depend upon the size of the globules.

This characteristic is determinable by a viscosity test, the viscosity being greater the larger the caoutchouc globules. The viscosity is tested by dissolving a definite amount of rubber in benzol and comparing the time which such a solution requires to drop through an orifice with the time taken by pure benzol. The usual strength of solution is 1 g. of rubber in 100 cc. of benzol.

When two samples of hevea rubber are identical both chemically and in viscosity, they are to all intents and purposes identical, whatever their origin, *i.e.*, they will make up into compounds of

identical insulation resistance, tensile strength, elasticity and life. Furthermore, experience has shown that rubber of high viscosity is superior to that of low viscosity.

Plantation rubber of high quality, especially smoked sheets, is not only chemically indistinguishable from fine Para rubber, but has substantially the same viscosity.

Plantation rubber has not always been equal to Para rubber in regard to viscosity. This property depends upon the age of the trees from which rubber latex has been derived, the size of the caoutchouc globules—and hence the viscosity—being greater the greater the age of the trees. When plantation rubber was first produced, the newness of the trees resulted in the production of rubber of low viscosity, but this condition no longer exists, the plantation trees from "selected estates" having reached an age where the rubber globules have approximately reached their maximum size as found in old forest trees.

In view of the above statements, compounds made from plantation rubber as produced many years ago will not have the quality of compounds made from recent plantation rubber. Hence the relative merits of wild and plantation rubber cannot be deduced from comparative life tests of compounds made many years ago from those two classes of rubber. The most convincing criteria for comparison, apart from theoretical considerations, are accelerated aging tests on compounds made within the last few years.

Such aging tests confirm the conclusion that compounds made with the best smoked sheets are more than equal in life to those made of the best wild rubber commercially available. Researches by Beadle and Stevens have shown that plantation rubber is not injured as much as wild rubber in the processes of manufacture. To this may be added the obvious fact that a wild product collected and prepared without supervision cannot be relied upon to have the same uniformity as one prepared by a scientifically controlled process.

The most usual fillers (*i.e.*, hardeners) are whiting, talc, zinc oxide, magnesium carbonate and litharge. A typical high-grade compound of the type having a preponderance of mineral fillers is composed as follows:

Ingredient	Per Cent by Weight
Hevea rubber	32
Whiting	23
Zinc oxide	36
Litharge	5
Sulphur	2
Paraffin wax	2
	100

When softeners are used in considerable proportions, care must be exercised in selecting them for permanence. For this reason, reclaimed rubber, which has gone through most of the vicissitudes it is likely to encounter, is preferable to such substances as oxidized oils, which are liable to further alteration.

VARNISHED-CAMBRIC-INSULATED CABLES

Varnished cambric is made of muslin coated with a special varnish. Most of the cable manufacturers purchase this material ready-made from specialists in this line, as the manufacture of varnished cambric is an art in itself. Very little has been published about the component materials of the varnish, but it is known that a linseed-oil base is used, mixed with asphaltic hydrocarbons.

In making varnished-cambric cables, the layers of tape are separated by a compound known as "slipper," which is either pure petrolatum or petrolatum compound with rosin and other materials.[1]

[1] Certain commercial specifications call for the use of a "slipper" of the same specific capacity as the varnished cambric itself. This is unattainable, even approximately, with the materials now available.

CHAPTER IV

BARE-WIRE MANUFACTURE

WIRE DRAWING

Copper rods are received from rolling mills ¼ in. in diameter and up. They are covered with black scale, which is removed by immersion in dilute sulphuric acid (10 per cent commercial acid).

In order to make the processes continuous, the rods are scarf-joined with silver solder and then fed to the drawing machine.

The process of wire drawing consists in pulling the rod through a succession of chilled cast-steel dies of decreasing diameter. The dies are kept in rotation. They are lubricated by water containing soap and tallow. The wire is taken off in coils or on reels.

The most usual practice is to make the steps correspond as far as practicable with regular A. w. g. sizes. Thus, in making No. 14 wire the successive diameters would be as follows:

Reduction	Diameter	Size, A. w. g.
Rod	0.250	
First	0.185	
Second	0.155	
Third	0.128	8
Fourth	0.114	9
Fifth	0.102	10
Sixth	0.091	11
Seventh	0.081	12
Eighth	0.072	13
Ninth	0.064	14

No. 14 wire is the smallest size wire allowed by the National Board of Fire Underwriters, except for cords, and is the size used for single circuits in house wiring. By far the greater part of the wire drawn is of this size.

The usual practice in drawing is to feed the rod at a speed of 46 to 59 ft. per minute, so that the wire comes out at from 700 to 900 ft. per minute.

The wire, as drawn, is hard and stiff. It is unsuitable for insulating and handling, and has low conductivity. It is therefore softened by annealing, which is accomplished by heating to 560° C. (1,050° F.) for 1 to 1½ hr. in an annealing furnace.

In one type of annealing furnace, the charge of copper is placed on an elevator platform, which is lowered, rotated and elevated into the furnace. In another type the charge of copper is placed on an elevator platform, lowered and the furnace slid over the elevator, which is then raised.

Wire which is to be insulated with rubber has to be tinned in order to protect it against corrosion by the rubber, and in order to protect the rubber from softening. The wire is therefore run into an acid bath to clean it and then into a flux. The acid bath usually consists of 8 per cent commercial hydrochloric acid, and the flux of 36 per cent commercial zinc chloric. Between the two there is a bath of running water to save the flux from contamination with acid. The wire is held under the tin by a submerged roller and is drawn through by power-driven winders at the receiving end.

The surplus tin is wiped off by rubber, cotton, or asbestos wipers.

STRANDING

Wire to be stranded is placed on reels which are suspended on trunnions along the axis of a revolving steel cylinder. The wire from each reel except one is run to the periphery of the cylinder, and the wire from that one reel runs through the center of the cylinder. The former wires are then twisted around the latter.

A type of machine used for larger conductors, especially those of sector shape, consists of reels carried on trunnions at some distance from the axis of rotation of the machine. These reels rotate about the axis and lay the wires around a central core wire. High-speed machines of this type are used for small sizes of wire.

CHAPTER V

THE MANUFACTURE OF RUBBER-INSULATED WIRE

PREPARATION OF COMPOUND

Rubber is usually received from the plantations in smoked ribbed sheets, about 36 by 14 in. in size and 0.15 in. thick. About 125 of these sheets are pressed together and packed in burlap. Except for the outer layers, these sheets are clean and pure, so that, if the outer surfaces are cleaned or removed, the rubber does not need washing.

Wild rubber is received from Brazil in biscuits about the size and shape of a football or larger. These are contaminated with bark, gravel, sticks, etc. and are therefore macerated to sponge-like sheets in the presence of running water, which washes out most of the impurities. The water gets into the rubber, which therefore has to be dried in a hot room for several days, the time depending upon the temperature. At least one manufacturer finds it advisable to use such a low drying temperature that the time of drying extends into months.

The dry sheets are weighed and placed on the mixing rolls or in a mixing machine, with the proper proportions of fillers and softeners, but without vulcanizing agents. Batches of Code compound from 50 to 100 lb. can be mixed in from ½ to 1 hr. The higher grade compounds take half as long again to mix.

When thoroughly mixed, the compound is taken off in sheets about ⅝ in. thick, and stacked up. The compound is then passed through a strainer, about 36 mesh, in order to remove any foreign particles which may have been in the ingredients or picked up in process. The compound emerges from the strainer in long strings, which are placed on mixing rolls and mixed with the vulcanizing agents, *i.e.*, sulphur and accelerators. These agents are best put in at this time instead of with the fillers and softeners, as there is then less likelihood of the compound being injured by premature vulcanization.

The sheets of compound from these rolls are again stacked up. When ready for use, they are warmed and softened in the mixing rolls and cut into bars.

APPLICATION OF COMPOUND

From this point there are two processes, the strip and the tubing processes. In the former the rubber is cut into ribbons, the ribbons laid parallel to the copper, wrapped around it and the sides joined by pressure. Two or more such strips are superimposed. In the latter process, the wire is passed through a large die and the compound forced around it through the die.

In order to make the ribbons for the strip process, the compound is calendered into thin sheets by passing through hot rollers. The first pair of rollers spreads the compound into a sheet and the second pair compresses the sheet and smooths its surfaces. Sometimes a third pair of rollers is used to improve the surface further.

Different manufacturers use a paper, cloth, sheet metal or powder separator between layers of compounds. The rubber sheet and its separator are cut into strips and each strip wound on a separate bobbin. The strips are then fed into a pair of wheel-like cutters between which the wire is rapidly drawn. The strip is thereby bent around the wire, its sides brought together and pressed firmly into contact. Sometimes two strips are used, one above and one below the wire, and the strips are united at two seams.

In the tubing process, the bars of compound are fed into a machine similar to a meat chopper, having a revolving screw which forces the compound to one end and drives it through a die under great pressure. The wire is being pulled through the center of this die, so the compound is formed around it like a tube.

It is usual to use the tubing process for small wires and the strip process for large ones, the size at which one process is better than the other being a matter of opinion and depending upon the details of the machinery available.

Whichever process is used, the larger sizes must be covered with a tight tape to conserve the concentricity of the insulation during vulcanization. This tape may be a permanent one made of rubber-filled muslin, or a temporary one made of heavy tin-foil, which is removed after vulcanization.

Small wires are wound in coils in iron pans, powdered talc being used to prevent adhesion between adjacent turns. Large wires and cables are wound on iron drums.

VULCANIZATION

In order to vulcanize the insulation, the pans or drums are placed in a cylindrical oven resembling a boiler, except that there is a door at one end. Dry steam is admitted under a pressure of 25 to 50 lb., corresponding to a temperature of 267 to 298° F., and the pressure slowly raised at the rate of 1 lb. per minute until the maximum temperature is reached. The steam is shut off after a prescribed period at this temperature, and the wire is allowed to cool slowly.

The time of vulcanization is determined by means of experimental charges vulcanized for different periods. These are submitted to an accelerated-life test and the period corresponding to maximum life is adopted for regular operation.

The accelerated-life test is made by submitting the samples to moving air at 70° C. for 96 hr. when the compound will be found to have deteriorated mechanically (*i.e.*, in tensile strength and elasticity) to the same extent as it would at ordinary temperature in two years. This test is known as the Geer test.

After vulcanization (pan-vulcanized) the wire is depanned and wound on reels. At this stage it is usual to "spark" the wire, *i.e.*, submit it to a very high-voltage test, by passing it through a copper helix maintained at several thousand volts above ground. If any dielectrically weak spot passes through the helix, a spark occurs. The wire is stopped and patched. Some manufacturers also "spark" at the insulating machines, *i.e.*, before vulcanization.

Rubber-insulated wire is either braided or lead-covered, usually the former, unless for voltages of 2,000 and over, when lead is necessary.

DETERIORATION

Rubber insulation deteriorates in the course of time, by oxidation, which hardens it and renders it brittle. Oxidation is hastened by heat and by ozone. The A.I.E.E. limits the permissible continuous operating temperature to 60° C. for low-voltage cables, but at high voltage this limit is reduced by ¼° C. for each kilovolt of working tension. Thus at 12 kv. the maximum permissible operating temperature would be 57° C.

At high voltages, corona in air within, or adjacent to, the insulation will generate ozone, which rapidly attacks the rubber. Hence it is of the utmost importance to protect the average rubber insulation from contact with air. Some compounds, however, are less subject to ozone than others and it is now

possible to obtain, from certain manufacturers, insulation which is but little affected by corona.

SPECIFICATIONS

Rubber insulation is purchased under standard specifications which determine its grade.

By far the greatest amount is purchased under the specification of the National Board of Fire Underwriters. This organization authorizes the Underwriters' Laboratories to inspect wire at the factories and to affix seals of approval. Monthly lists of demerits are sent to each manufacturer, listing all the manufacturers, but using letters in place of names. Each manufacturer is told which letter designates him, but no key is given to the other letters. The cost of this service is borne by the manufacturers. This specification requires a minimum of about 20 per cent of rubber gum and contains various electrical and mechanical test requirements of a rather moderate character. A condensed version is appended. Wire made according to this specification is commonly called "Code wire." The commonest size of Code wire is No. 14, which is used for all circuits in house wiring which do not carry more than 600 watts.

The higher grade of insulation, known as the 30 per cent hevea grade, is made according to the specifications of the A.S.T.M. The chemical requirements of this specification were formerly known as the specification of the Joint Rubber Insulation Committee. This specification requires the use of from 30 to 33 per cent of new hevea rubber and excludes all other organic substances except 4 per cent waxy hydrocarbons. This compound is found to have a long life except when exposed to ozone. For this reason it should always be used under lead for voltages of 2,000 and over, unless a very thick wall is used which is applied firmly to the conductor.

The railway signal engineers have a special specification, which gives the formula of the compound and calls for wild rubber. Most of the railroads, however, purchase special grades of wire by trade name rather than by specification.

Condensed Specification of Code-grade Rubber-insulated Wire

For working pressures up to 600 volts

Conductor.—Soft annealed copper, tinned. Stranding, A.I.E.E. standard concentric, except that all wires smaller than No. 6 are solid unless otherwise specified.

Rubber Compound.—At least 20 per cent rubber of the quality required under "Chemical Tests." (The proportion of rubber is not actually stated but is to be inferred from the chemical tests specified.)

Thickness of Insulation

Size	Sixty-fourths of an Inch
No. 14 to 8 A. w. g. (B.&S.)	3
6 to 2	4
1 to 0000	5
225,000 to 500,000 cir. mils	6
525,000 to 1,000,000	7
1,250,000 to 2,000,000	8

Physical Properties

	Wall smaller than 5/64 in.	Wall 5/64 in. and larger
Tensile strength, pounds per square inch	500	500
Elongation at rupture, not less than	6 in.	5 in.
Stretch from 2 in. to	5 in.	4 in.
Recovery after stretching as specified above	2½ in.	2½ in.

Chemical Tests

Five chemical determinations made on the rubber compound shall not exceed 80 per cent:

Acetone extract.
Alcoholic potash extract.
Chloroform extract.
Ash.
Total sulphur.

Voltage Tests

For wires and cables not over 600 volts working pressure; one-minute test after 12-hr. immersion

Size	Test Voltage
14 to 8 A. w. g. (B. & S.)	1,500
6 to 2	2,000
1 to 0000	2,500
225,000 to 500,000 cir. mils	3,000
600,000 to 1,000,000	3,500
Over 1,000,000	3,500

INSULATION RESISTANCE

Megohms after 12-hr. immersion

Size	Megohms for 1,000 ft. at 60° F. (15.5° C.)	Size	Megohms for 1,000 ft. at 60° F. (15.5° C.)
14 A. w. g. (B.&S.)	1,500	225,000 cir. mils	500
12	1,250	300,000	500
10	1,125	400,000	500
8	1,000	500,000	500
6	1,000	600,000	500
4	750	700,000	500
2	625	800,000	500
1	750	900,000	500
0	625	1,000,000	500
00	625	1,250,000	500
000	500	1,500,000	375
0000	500	1,750,000	300
		2,000,000	250

Braid.—Unless otherwise specified, all wire smaller than No. 6 shall be single-braided. Size No. 6 and larger shall have one tape and one braid.

CHAPTER VI

MANUFACTURE OF IMPREGNATED-PAPER AND VARNISHED-CAMBRIC-INSULATED CABLES

IMPREGNATED PAPER

The manufacture of impregnated-paper cables consists only of wire drawing, stranding, taping, cabling, drying, impregnating and leading. Each of these processes, however, requires the most elaborate study, long experience and a smoothly working organization in order to perform them successfully.

The following brief description is intended to give an outline of current practice, without any analysis or expression of opinion as to the relative merits of the variations adopted by different makers.

Impregnated-paper cables are practically always stranded, so that, after the copper wire has been drawn, it must be stranded into either circular or sector cross-section. In the latter case, the sector form may be given either in stranding or by subsequent deformation of the concentrically stranded conductors.

The process of taping, *i.e.*, applying the paper, is performed on machines which rotate bobbins of paper tape around the slowly advancing conductor. The tape unwinds from the bobbins as the latter rotate. Each machine has from 16 to 72 heads, sometimes all revolving in the same direction and sometimes having alternate pairs or threes in opposite directions. The speed of taping is from 10 to 22 cable ft. per minute. Machines for higher speeds have recently been developed. The applied paper is sometimes pressed tight either by dies or snuggers, after each group of tapes.

Paper may be applied in either an overlapping or an open helix. In the former construction, known as lapped taping, the paper has to be wound on a cone, and therefore one edge has to wrinkle while the other stretches. A paper taken from a lap-wound cable has a curved appearance. In the latter construction, known as butted taping, the paper is wound on a cylinder and the two edges receive equal tension. Hence, a

paper taken from such a cable would be perfectly straight. Butted papers are favored in England and France, lapped papers in Germany and Switzerland. American practice favors lapped papers, but both kinds are made. Tests of the two types reveal little or no difference in electrical or mechanical qualities.

The next process after taping, in the case of multiple-conductor cables, is cabling, *i.e.*, assembling the separate conductors with their fillers and either holding the group together with a paper or muslin binding tape or applying the belt at once. The drums of single-conductor cable and of fillers are suspended on trunnions in a rotating frame and the insulated conductors, as they unwind from the drums, are carried along the frame to a closing die, into which they enter with the fillers, and are twisted together in a long helix. In the case of sector cables, special provision has to be made at the cabling machine for keeping the inner edges of the sectors pointing toward the axis of the cable as the conductors are brought together.

The next step after cabling is the application of the belt, which is done on a machine similar to that used in taping the individual conductors.

The cable is now ready for the important process of drying. There are three methods now in use. The oldest is to place the reel of cable in a tank lined with steam pipes, heat it until hot throughout, close the lid of the tank and subject to a vacuum. This process has been largely superseded by two others. In one of these processes the cable is heated in an air oven until nearly all the moisture has been turned into steam, and then the steam is removed by quickly placing the cable in a vacuum tank. Drying is performed at temperatures near the boiling point of water, *i.e.*, from 95 to 105° C. In the other process the cables are heated in vacuo electrically, *i.e.*, by passing strong currents through their conductors until all moisture has been vaporized. These last two processes are in successful operation in making the best cables.

All these processes end in the vacuum tank, which is also the impregnating tank. When the drying is complete, and the air removed from the cable, as far as practicable, the impregnating compound is drawn in and the dried paper saturated therewith. Some impregnate in vacuo, some under pressure and some initially in vacuo with a final pressure period.

The weight of oil which paper can be made to absorb depends upon the specific gravity of the oil, the compactness of fibers in paper and a little-understood characteristic of the fibers. The weight which is actually absorbed also depends upon the time of impregnation, the viscosity of the oil at the temperature of impregnation and the mechanical condition of the paper.

The amount of oil retained on the surface of the paper depends upon the character of the surface, the looseness of application, the surface tension of the oil, and certain precautions in manufacturing, with special reference to the removal of air.

The speed of impregnating is greatly influenced by the viscosity of the compound, being, of course, greater the lower the viscosity. The time of impregnation is usually from 12 to 36 hr., and various manufacturers use temperatures from 85 to 130° C.

Upon completion of the impregnating, the cable is either cooled in the tank, or taken out hot and put in a special cooling tank, or taken out hot and put in a tank from which it is run into the lead press without cooling. Some manufacturers remove the cable while hot and permit some of the oil to drip out before applying the lead, an obviously poor procedure.

Whichever process is used, it is important to lose as little as possible of the compound before the cable is fed into the lead press.

Lead is fed into the lead-press cylinder in the molten state. As soon as it solidifies, an hydraulic piston puts it under pressure and squeezes it through an annular die. The cable is passed through the center of this die, and the lead is squeezed tightly around it. The cable is now complete and ready for test.

These processes offer many opportunities for producing a bad cable without any defects being evident. Hence, the most careful controls are necessary at all stages. A conscientious manufacturer will keep continuous records of the numerous features which effect dielectric strength, dielectric loss, saturation and flexibility.

VARNISHED CAMBRIC

Varnished-cambric, also known as varnished-cloth insulation, is applied helically to the conductor in strips much like paper. The only difference is that the "slipper" compound, which is mostly petrolatum, either is applied over each layer of tape by means of jets on the taping machine itself, or is put on the tape beforehand.

Most varnished-cambric cables are covered with one or two saturated cotton braids such as are used on rubber-insulated wires. They are, however, sometimes provided with a lead sheath.

Low-voltage varnished-cambric cables are often used as risers in large buildings and it is usual to omit the slipper from between the two innermost layers of tape in order to prevent it getting among the copper strands and dripping out into junction boxes, etc. on the lower floors.

CHAPTER VII

INSTALLATION AND SPLICING OF UNDERGROUND CABLES

INSTALLATION

In the United States underground cables are commonly installed in tile or fiber ducts. These are usually about 3½ in. square or 3½ in. in diameter, although diameters as low as 3 in. and as high as 4½ in. are to be found.

Preliminary to installing a cable, the duct must be wired, by which is meant that an iron wire, usually No. 10 B.w.g., is pulled into the duct by means of a steel snake or duct rods. When a cable is to be installed, a rope is attached to this wire and the wire drawn out, pulling the rope into the duct. The cable end is

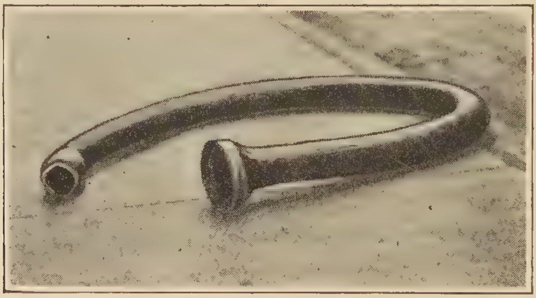

Fig. 2.—Bolony for installing underground cables.

then attached to the rope and the rope pulled out, thereby drawing in the cable. The details of this procedure have been revised in the last few years and it will be of interest to study them.

Pulling rope should have hemp woven among the steel strands and should be covered with hemp, to protect the wires from abrasion and the hands of the men from being pricked or scratched by broken wires.

The best practice is to feed the cable into the duct through a guiding tube or "Bolony," which is flexible steel steam pipe

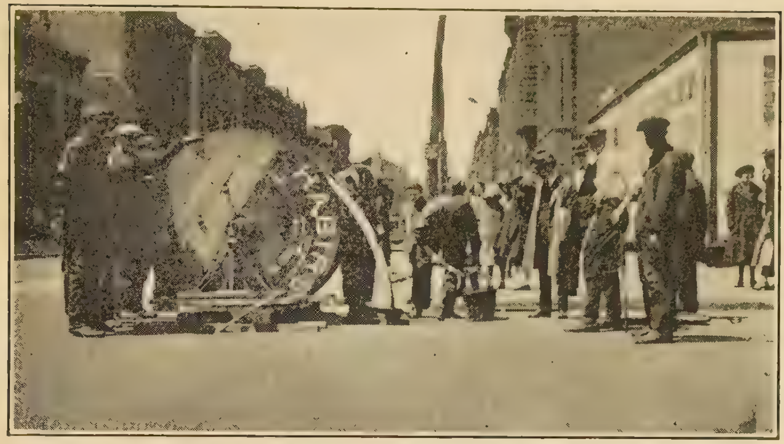

FIG. 3.—Installing cable with bolony.

FIG. 4.—Clevis attached to cable.

about 4 in. in diameter, one end of which is equipped to fit into the duct, and the other provided with a funnel, into which the cable is fed (Figs. 2 and 3).

The end of the cable may be gripped either by a woven cable grip, which is satisfactory only if the lead sheath is tight, or preferably by a clevis, which is satisfactory even if the sheath is loose (Fig. 4).

The principle of the woven cable grip is that the wires are in the form of an open weave which, when pulled longitudinally, will contract laterally and thus hold fast to the sheath.

The clevis is attached to the conductor and sheath and, therefore, affords a much firmer hold. The pulling rope is usually

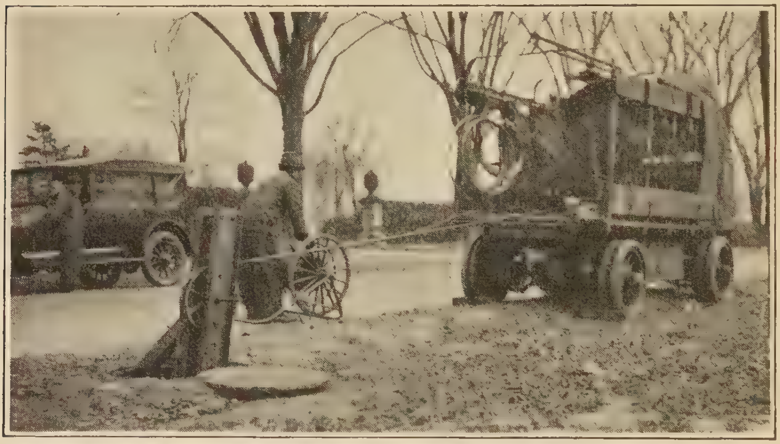

Fig. 5.—Drawing cable by motor, using parallel bars.

drawn by a gasoline engine-driven drum on a truck. In the most approved practice the rope is run over two pulleys attached to a pair of channel irons, called parallel bars. The pulleys may be placed at any of the holes shown in the channels in order to obtain a straight pull from any duct (Fig. 5).

The usual net speed of drawing large cables is about 1 ft. per second, but the practical conditions of installation usually make it impossible to draw in a length at more than half that speed.

It is of great importance with high-voltage cables to train the cable carefully around the walls of the splicing chamber, as sharp bends are not only liable to tear the paper but also to create voids between the paper tapes and between the paper and lead.

Park cables, *i.e.*, cables armored with steel tape, are laid without ducts, at a depth of 18 to 24 in. It is usual to make a trench by means of a caterpillar trenching machine, lay the cable and refill the trench. Splices are enclosed in cast-iron boxes.

SPLICING

Because of the limited length of cable which may be installed in conduits, it is necessary to make a splice every 300 or 400 ft. Such splices are made in splicing chambers or manholes, where the conditions make it difficult to apply clean, dry insulation.

When it is remembered that the electrical function of the paper in a cable is to serve as a baffle for the oil, and that this paper must be removed at splices, it is clear that the insulating problem at a splice is to reconstruct an effective ion baffle not only without the facilities of a manufacturing plant but in a splicing chamber where the working conditions are particularly unfavorable.

The problem is made fundamentally difficult by the fact that impregnated paper is very much weaker dielectrically along than across its surfaces. Hence, it is very important to design high-voltage splices so that the lines of electric force from the conductors shall not run parallel to the surface of the paper at any place. This fact is just beginning to be appreciated and many splices are defective because it has been neglected.

Another general fault is too great an angle between conductors of triplex cables, where the conductors are separated for splicing purposes. This results in failure at or near the crotch.

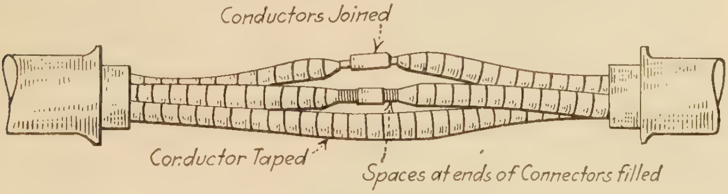

Fig. 6.—Taped joint (Nela type).

The details of connecting the ends of the conductors are common to all types of splices and will be considered before taking up the different methods of insulating.

After the ends of the cable to be joined are opened and the insulation removed from the individual conductors, the latter are so arranged that the ends of the bare copper butt squarely

together. The copper should be carefully cleaned with gasoline and the strands tinned. A split soft-copper sleeve of about the size shown in Table II is then slipped on. This sleeve must be of sufficient length to extend far enough each side of the joint to make substantial electrical and mechanical contact. It is beveled down at each end so as not to leave any sharp edges. The sleeve is then carefully and gently hammered down so as to fit snugly around the strands of the conductors, and the whole is gone over with a file, if necessary, to smooth it off, great care being taken to get rid of all filings. The sleeve is then soldered in place and all excess solder carefully wiped off (Fig. 6).

Joints may be divided into three general classes, according to the type of insulation:

1. Taped joints, which have hand-applied insulation around the varnished-cambric tape.
2. Baffled joints, which have ready-made baffles between the joined conductors. These may be impregnated-paper tubes, bakelite or micanite separators.
3. Taped joints with machine-applied tape.

TAPED JOINTS—ORDINARY TYPE

The general principle involved in taped joints is to replace the insulation which has to be removed in order to join the copper conductors, by hand-applied paper or varnished-cambric tapes, depending on the insulation of the cable.

A typical method of doing this is as follows: After the cables have been properly arranged in position in the manhole, 8½ in. of the lead sheath for 13,200-volt cables and 10 in. for 26,400-volt cables is cut off from each end. The belt insulation is then removed to within ¾ in. of the lead and 1½ in. of paper is cut from around each conductor.

The lead sleeve is then slipped over one end and the sheath slightly belled away from the paper jacket so that there will be no sharp edges for static discharges. Lead sleeves should be 20 in. long for 13,200-volt cables and 24 in. long for 26,400-volt cables. The copper sleeves are then sweated to the conductors, as already explained.

A step is next made in the insulation around each conductor by removing one-half the thickness of paper for a distance of 1 in. Instead of making this step, the paper is sometimes beveled or "penciled" (Fig. 6). Stepping is preferable where the joint

is made with paper tape, and penciling where varnished-cambric tape is used. Paper is liable to tear if applied to a penciled surface. The exposed paper is then boiled out by pouring oil over it, at 125° C., so as to remove moisture. The space between the end of the copper sleeve and the end of the paper insulation is filled in with a wrapping of narrow cotton tape previously boiled in paraffin. After the ends have been thus filled, a single layer of cotton tape is applied over the copper connector or sleeve and the whole again boiled out with paraffin.

The space between the ends of the original insulation around each conductor is filled even with the copper sleeve with a wrapping of varnished-cambric or impregnated-paper tape. The tape is given one-half overlap and is pulled tight to exclude air, petrolatum being applied between successive layers.

Additional impregnated-paper or varnished-cambric insulation is applied over the preceding to a thickness equaling 40 per cent of the original insulation. This is accomplished by starting about 3 in. from the belt insulation and winding the tape back and forth in such a way that the ends are tapered. There is no application of petrolatum in this case.

When three individual conductors have been joined in this way, they are spread apart by means of a roll of tape ½ in. in diameter located at the center of the joint. Belt insulation may be applied by a wrapping of oiled-paper or varnished-cambric tape to the same thickness as the original belt insulation. The ends of the latter may or may not be penciled, but penciling has the advantage of not leaving any sharp angles more or less difficult to fill, and of making the union between original and hand-applied insulation more homogeneous. Holes are punched through the belt between the individual conductors so as to permit the entrance of compound between them.

The next operation is that of wiping the lead sleeve in place, care being taken to properly center it over the joined conductors. The final operation consists of filling the sleeve with compound. The temperature at which the compound for filling the sleeve should be poured in varies according to different authorities. It should be hot enough to boil out moisture but not hot enough to injure the insulation. Different companies recommend a temperature from 100 to 150° C. The Habirshaw Electric Cable Company recommends a mean of about 130° C. as sufficient to drive off moisture but still low enough to allow a margin

of safety against burning the insulation, in case a workman should be a little careless.

The Underground Systems Committee of the N.E.L.A. has adopted a specification embodied in the *Proceedings* for 1921, for making hand-wrapped joints on 24,000-volt 1/0 and 2/0 three-conductor cables where the insulation is 9 by 7/32. The distinctive feature of this joint is that the belt insulation is omitted.

The joint is, briefly, made up as follows: 9 in. of the lead sheath is removed and the edges belled out about 1/4 in. The belt insulation is entirely removed up to 1/2 in. from the lead sheath and 1 in. of insulation removed from each conductor. The remaining insulation is penciled back for 1 1/8 in. so as to leave a smooth surface, which is protected by a cloth during the operation of sweating on the copper connectors.

The first step in building up the insulation is to fill up the depression at the end of the copper sleeve with impregnated cotton twine, smoothly and without ridges. The twine is then covered over with a liberal application of compound. The joint is next tightly wrapped with impregnated-paper tape 1/2 in. wide, with an application of compound over each successive layer, to a thickness equal to the original factory insulation. Tape 1 in. wide also with petrolatum between successive layers is next applied for a length of 10 in. along the conductors and 6 in. at the top to a diameter of 1 1/2 in. To separate the conductors properly, a band of tape is wound around the taped conductors to a diameter of 1 3/4 in. A short wrapping of tape is applied around the three conductors projecting from under the belled lead to a point not over 1 1/2 in. from the lead sheath. The lead sleeve is wiped and filled similarly to the form of joint described above.

ROLLED-PAPER JOINTS

A recent type of joint is made by penciling the ends of the paper on each conductor and filling up with varnished-cambric tape to the level of the original insulation. Sheets of paper about 8 in. wide are impregnated in cable compound and wound over the joint while the compound is soft. The paper is rolled on tightly until the desired thickness is obtained. The sheets are narrower at one end than at the other, so that the finished roll on the joint has tapered ends.

RELATIVE MERITS OF VARNISHED-CAMBRIC AND PAPER TAPES

Some power companies use varnished-cambric tapes exclusively for making hand-wrapped joints even with paper-insulated cables. The reason for this is that the glazed surface of the varnished cambric does not absorb moisture as readily as paper. Also, since varnished cambric is stronger than paper, it may be pulled more tightly in wrapping, which is important for excluding air and moisture. Its advantage for penciled insulation has been pointed out.

BAFFLED JOINTS

There are several kinds of joint baffles, the most important of which are the Conducell, made of micanite, the impregnated-paper tubes made by the Standard Underground Cable Company and the shields, made by the Bakelite Company.

The object of using baffles is to obviate the necessity of replacing the removed factory insulation entirely by a hand-wrapped insulation. They all consist essentially of two elements—one which keeps the conductors separated from each other and one which separates them from the outer lead sheath and acts as belt insulation. A wrapping of varnished-cambric tape should be placed over the copper sleeve. The details of making up a joint according to this method are extremely simple and quickly accomplished, thus reducing the liability of electrical weakness to a minimum. It is obvious that the liability of dirt and sweat from the splicers, with the resultant electrical weakening of the splice, is vastly less in making up this type of joint than with the long painstaking operation of hand wrapping within the confined space of a more or less dirty manhole where dust can blow in from the street. The cost is comparatively low.

With joints of this type the filling compound is of even greater importance than in other types, as it not only excludes air and moisture but also acts as the principal insulator. It must flow readily at a temperature not high enough to injure the insulation and must remain hard at the highest allowable operating temperature of the cable, but it must not become brittle at low temperatures or harden so rapidly that air or moisture which is being boiled out of the splice will become confined and make it honeycombed.

Conducell joints are used for voltages as high as 25,000 and as low as 6,600 volts (Fig. 7). Black varnished-cambric tape, with-

out extra compound is wound around the spliced copper conductors to a thickness equal to that of the paper insulation. The original paper insulation is "penciled" (beveled) at the ends to avoid sharp edges and to facilitate the application of the varnished-cambric tape. The joints are not boiled out. Some companies do not use the wrapping of varnished-cambric tape or even pencil the original insulation, but leave the copper bare. Others pencil the paper insulation and wrap two or three layers of dry varnished-cambric tape around the bare copper. This wrapping does not add materially to the cost of the joint and is well worth while.

After the porcelain separators have been put in place a few inches each side of the spliced conductors prepared as described above, the micanite elements of which the Conducell is composed

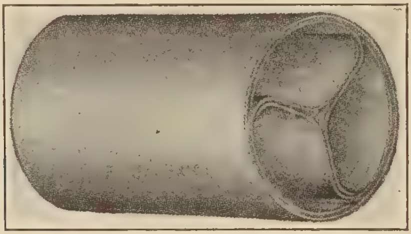

Fig. 7.—Baffles for Conducell joint. Triplex cable.

are put in place. The splice is filled with a special compound known as Conduline.

IMPREGNATED-PAPER TUBES

Impregnated-paper tubes do not seem to be much used for voltages higher than 13,200 and are being displaced by micanite or bakelite baffles. There are, however, some instances where paper tubes have been used for 25,000 volts.

With this type of joint it is, of course, necessary to strip off the paper belt, and consequently the lead sheath farther back on one side of the joint than on the other, to permit of the tubes being slipped on before the copper connectors are soldered. As it must be possible to slip the tube far enough back to make it possible to join the copper conductors, it will be necessary to remove the original belt insulation far enough back to permit of the tube being pushed clear of the stripped copper. This procedure is unnecessary with the more modern baffled joints,

because the baffles around the individual conductors are slipped in between the conductors. The outer element, consisting of a cylindrical tube large enough to surround all three conductors with their individual baffles is, in all types, slipped over one end of the joint similarly to the lead sleeve, before the conductors are joined.

The insulation is penciled where it has been cut back and the bare copper covered with a layer of hand-applied varnished-cambric tape or paper, depending on the kind of insulation used for the cable. No extra petrolatum is used between the layers of this hand-applied insulation and there are no spreaders between the conductors such as are used with Conducell joints.

The impregnated tubes are then slipped over each of the three joined conductors and the large tube over the three small ones and the splice is ready for the lead sleeve.

VACUUM JOINTS

The vacuum joint is used by the New York Edison Company for high voltage cables. The object of this method of jointing is to make possible the use of a filling compound (petrolatum) which is soft at low temperatures and which will therefore fill in crevices and not crack or contract but at the same time not drain away into the cable. This joint meets these conditions and is successful, especially for high voltages, but has the disadvantage of being very expensive to make. This expense is probably justifiable for 25,000-volt cables but where voltages as low as 13,200 volts are concerned other types of joint seem to be fully adequate and moreover much more economical.

The following is a brief description of how the vacuum joint is made: About 10½ in. of the lead sheath is removed from the cable, which is divided up about as follows: 9 in. of the belt is removed and 3 in. of the insulation around each conductor. This leaves 1½ in. of belt insulation. The three conductors are connected with copper sleeves in the usual way and the insulation around each conductor as well as the belt is penciled so that there will be no difficulty in winding on the paper tape smoothly. The lead sheath is also belled out a little from the core.

One layer of paper is then removed from belt to conductors so as to get rid of all possible filings or dirt. Paper tape is next wrapped around each conductor singly by hand, starting at the center of the copper sleeve, working back in each direction to the

belt and in such a way as to make the hand-applied insulation somewhat thicker over the sleeve than normal and tapering down towards each end. After each layer of paper is applied, a liberal amount of petrolatum is spread on and the following layer of paper pulled down fairly tight so as to squeeze out bubbles of air.

After the three conductors have been insulated in this way, the spaces between them are filled with vacuum-dried impregnated jute and quantities of petrolatum to make a round cross-section. Paper tape is then wound around this in the same manner as for each conductor, starting from the center and working in each direction towards the lead sheath.

In order to permit the entrance of compound from the lead sleeve into the interior of the joint and also to permit the escape of air, six holes are bored through the hand-applied paper belt. The holes are in the spaces between conductors and there are two groups located respectively one-third the length of the joint from the "belled" lead sheath.

One of the distinctive features of the vacuum joint is the copper-wire gauze "stocking" which is placed over the hand-applied belt. Its ends extend under the belled ends of the lead sheath, which are beaten down over it. This stocking is supplied in the proper shape to conform to the contour of the splice and is split longitudinally to permit being put in place. The seam is then soldered. The function of the wire gauze is to preserve the metallic continuity of the lead sheath at an approximately uniform distance from the conductors, thus reducing disarrangement of the voltage gradient in the insulation to a minimum. This and the Cleveland splice described below, are the only kinds of splice which effectually keep the lines of electric force from running parallel to the surface of the insulation.

Several layers of cotton wick are wound over the "stocking" and saturated as full of petrolatum as possible. This acts as a reservoir of petrolatum to replenish any which may work away from the splice between the strands of the conductors.

The lead sleeve is then wiped. This sleeve has two openings. At one a vacuum pump is connected and at the other compound is forced in under pressure after the air and moisture have been exhausted. This operation is accomplished by means of a rather complicated system of pipes and valves, but is entirely practicable. These splices, however, are quite satisfactory without the use of vacumn. When the sleeve has been filled

the compound is allowed to cool, as a result of which it contracts somewhat. One of the holes is then sealed and more compound forced in at the other by means of a grease cup and piston which is screwed down.

THE CLEVELAND JOINT

There is a 66,000 volt, three-phase circuit at Cleveland, Ohio, composed of three single conductor cables, each operating at 38,000 volts to ground. The splice used on these cables presents several novel features which are likely to be incorporated in future work. These are the undercut of the insulation, the application of tape by means of a portable taping machine, and the use of a collapsible reservoir to provide for expansion and contraction of the compound.

The procedure in making this splice is as follows: About 3/4 in. of lead sheath and paper insulation is removed from the end of the cable. The insulation is then undercut at the end in conical form by means of a special cutting tool. A pair of 8 in. brass sleeves and a shellaced tube are then slipped over the cable far enough to be out of the way. There are two sets of sleeves, an inner set, attached to the conductor and an outer set which makes contact with the undercut surfaces. The pair of hollow brass connector sleeves is put into the conical spaces where the insulation has been cut. When these are in position, the cables are clamped together, forcing the outer sleeves in firm contact with the insulation. The inner connector is then sweated in place with solder and the outside one is filled with solder. The sheath is now removed for a distance of 12 1/2 in. each way from the center of the connector. Paper tape is then wrapped over the connector to a diameter of 4 1/2 in., extending 12 in. each way from the center of the connector. This is done by means of a special taping machine operated by hand. The taping compound, consisting of 40 per cent petrolatum and 60 per cent transil oil is poured over each layer before the next is applied, the temperature being between 220 and 240° F. The shellaced paper tube is put into position and fastened tightly with wedged spacers of the same material. The lead sheath is then removed the full length of the joint, that is, 18 1/2 in. each way from the center of the connector. Cotton candle wicking, impregnated with the taping compound is wrapped on each end of the joint, increasing the diameter of the cable to 5 1/4 in. at a distance of 4 1/2 in. from the end of the lead and decreasing

to the diameter of the paper wrapping at 10 in. from the end of the lead.

The wicking is forced under the belled lead at the end of the joint and the lead then beaten down on top.

The 8 in. brass sleeves are then placed in position and are drawn into close contact with the cotton wicking on each end of the joint. The sleeve is soldered at each end and in the center. The next step is to fill the sleeve with a compound at a temperature between 220 and 240° F. The reservoir is also filled and fitted on to the sleeve.

Table II

For cable No.	Length, inches	Thickness, inches
8	1	0.060
6	1	0.060
5	1¼	0.060
4	1½	0.060
3	1½	0.060
2	1½	0.060
1	1¾	0.060
100,000 cir. mils	2	0.075
0	2	0.075
125,000 cir. mils	2	0.075
00	2	0.075
150,000 cir. mils	2¼	0.075
000	2¼	0.075
200,000 cir. mils	2½	0.093
0000	2½	0.093
250,000 cir. mils	2½	0.093
300,000 cir. mils	3	0.125
350,000 cir. mils	3	0.125
400,000 cir. mils	3½	0.125
450,000 cir. mils	3½	0.125
500,000 cir. mils	4	0.125
550,000 cir. mils	4	0.125
600,000 cir. mils	4½	0.156
650,000 cir. mils	4½	0.156
700,000 cir. mils	4½	0.156
750,000 cir. mils	5	0.156
800,000 cir. mils	5	0.188
900,000 cir. mils	5	0.188
1,000,000 cir. mils	5	0.188
1,250,000 cir. mils	5	0.250
1,500,000 cir. mils	5½	0.250
2,000,000 cir. mils	5½	0.250

CHAPTER VIII

TESTING OF CABLES AND DETECTION OF FAULTS

Factory testing is performed for four distinct purposes: (1) to ascertain whether the materials of which cables are to be made have the requisite quality; (2) to ensure that every process in manufacturing is properly carried out; (3) as a last chance to catch defects which may have accidentally passed the second series of tests; and (4) to show whether the cable passes the customer's specifications. These last tests are known as the factory-acceptance tests.

FACTORY TESTS

The principal acceptance tests are described below.

High-voltage Test.—High-voltage tests are intended to detect weak spots in the insulation and to determine whether its dielectric strength is sufficient to enable it to withstand the voltage to which it is likely to be subjected in service, with a suitable factor of assurance. For the former purpose, it is obviously necessary to make tests on the entire lengths to be shipped; for the latter, it is better to make tests on short lengths, say 10 to 20 ft., which may be tested to destruction without excessive expense.

High-voltage tests are made by applying an alternating voltage of suitable magnitude between the conductor and sheath or water. The initially applied voltage must not be greater than the working voltage and the rate of increase must be approximately uniform, not over 100 per cent in 10 sec., and not under 100 per cent in 60 sec. The voltage must be applied for 5 min. unless the insulation breaks down before the end of that time.

The ideal way to make the high-voltage test is to use a three-phase equipment, which will simultaneously test between conductors and between all conductors and ground. This arrangement, beside being the most rapid method of testing, also most closely resembles working conditions. The Standards of the A.I.E.E., however, mention only single-phase testing. In this case each conductor of a multiple-conductor cable should be tested against the other conductors connected together with the

sheath or water. An exception is made in the case of three-conductor cables for use with grounded neutral and in which the belt thickness is less than the thickness of insulation of each conductor. In this case, each conductor should be tested against the other two with the sheath out of circuit but grounded, and then all three conductors simultaneously tested against the sheath. In the latter test the voltage would be $\frac{1}{\sqrt{3}}$ of that in the former.

The magnitude of the test voltage depends upon the specification under which the wire or cable is made. It should be at least two and one-half times the working voltage, and in the case of low-voltage cables the ratio must be much greater in order to enable weak spots to be detected.

The magnitude of the testing voltage for paper- or varnished-cambric-insulated cables is specified by the Standards of the A.I.E.E. as given in Table III. This rule, however, is modified by the Underground Systems Committee of the N.E.L.A. by the provision that the following rule shall apply if it gives a higher voltage than that of the A.I.E.E.

> The high-voltage test shall be made at a tension equal to $75 \times (t - 30)$, where t is the thickness of the insulation in mils.

Tests on short lengths of cable, that is, lengths of from 10 to 20 ft., are often based on twice or two and one-half times the tension permitted by the above rule, which applies to full lengths.

Whether tests are made with single- or three-phase tensions, either the center point or the neutral of the testing circuit should be grounded in order to avoid uncertain potentials between conductors and ground while voltage is applied between conductors.

The National Electrical Code and A.I.E.E. tests for rubber-insulated wires and cables are given in Table IV.

Megohms.—The insulation-resistance test is applied after the high-voltage test and in the case of rubber insulation, where this test originated, was intended primarily to reveal whether the high-voltage test has broken down the insulation. It also has a secondary purpose of revealing lack of uniformity in manufacture, as wires of a kind should be fairly uniform in insulation resistance. In the case of paper insulation, a small puncture is apt to heal itself and not show in the megohms test. The test is made by applying a voltage of from 100 to 500 volts, usually

from a dry battery, between conductor and ground, and measuring the leakage current after a 1-min. electrification, the conductor being maintained negative to the sheath or water.

In the case of multiple-conductor cables, the specified value of megohms is usually that measured from one conductor to all the other conductors in multiple with the sheath or water.

If a number of reels of cable are connected together and tested simultaneously, the average megohms are obtained, but some of the reels may be too low to pass specifications.

The megohms depend upon the temperature, being lower the hotter the cable. There are, therefore, certain temperature coefficients, by which the measured megohms are multiplied or divided in order to reduce them to what their value would be at a standard temperature, which has been arbitrarily selected as 60° F. (15.5° C.). Furthermore, the mile, or sometimes 1,000 ft., has been selected as a standard length for expressing megohms. It should be remembered that the megohms per mile of a cable are less than the megohms per 1,000 ft.

The galvanometer deflection will depend greatly upon the period of application of the test voltage. It will at first be quite large and then will gradually decrease to a small fraction of its original value. A period of 1 min. has been standardized in order to make tests comparable. Several theories have been advanced which will account for this phenomenon, some involving the assumption of polarization of moisture and others making use of the heterogeneous character of the insulation and consequent formation of internal charges on the surfaces of the particles of oil and paper. The latter theory seems to be more likely to be applicable to modern cables, as they are practically free from moisture. This matter will be more fully discussed in the next chapter.

Capacitance or Electrostatic Capacity.—A few purchasers call for tests of capacitance on impregnated-paper-insulated cables. Such tests are generally useless, as the capacitance does not vary greatly between cables of a given type.

The capacitance is expressed in microfarads per mile, corrected to a temperature of 60° F. (15.5° C.). The capacitance, unlike the megohms, is greater the longer the cable.

The capacitance of multiple-conductor cables is measured between conductors and also between each conductor and the other conductors connected to the sheath or ground.

TABLE III.—HIGH-VOLTAGE TESTS FOR VARNISHED-CAMBRIC OR IMPREGNATED-PAPER-INSULATED CABLES

Minimum values

Operating kilovolt	Test kilovolt	Operating kilovolt	Test kilovolt
Below 0.5	2.5[1]	5.0	14.0
0.5	3.0	7.5	19.5
1.0	4.0	10.0	25.0
2.0	6.5	over 10.0	2½ times operating pressure
3.0	9.0		
4.0	11.5		

[1] The minimum thickness of insulation shall be 1/16 in. (1.6 mm.).

TABLE IV.—HIGH-VOLTAGE TESTS FOR RUBBER-COVERED WIRES AND CABLES

(*a*) National Electric Code, 1-min. test

Size	Working voltage					
	600	1,500	2,500	3,500	5,000	7,000
14 to 8 A. w. g.	1,500	6,000	8,000	10,000	12,500	17,500
6 to 2	2,000	7,000	9,000	10,000	12,500	17,500
1 to 0000	2,500	8,000	10,000	10,000	12,500	17,500
225,000 to 500,000 cir. mils	3,000	9,000	10,000	11,250	12,500	17,500
600,000 and over cir. mils	3,500	10,000	10,000	12,500	12,500	17,500

(*b*) A.I.E.E. Standards, 5-min. test

One kilovolt per 1/64-in. insulation thickness up to 10/64 in. Above 10/64 in., 10 kv. plus 1.5 kv. per 1/64 in. up to 30/64 in. Where thickness is 16/64 in. or over, rule applies only to conductors as big as No. 6 A.w.g. The A.I.E.E. allows lower test voltage for working voltages up to 600 volts alternating current. In this case, the rule is as follows:

14 to 8 A. w. g.	3.0 kv.
7 to 0000	3.5 kv.
250,000 and larger	4.0 kv.

Capacity tests should be made with alternating current as direct current does not give the true capacity, but a complex quantity, depending not only upon the capacity but upon the

speed of testing, the temperature and the characteristics of the testing instruments. This subject will also be discussed at greater length in the next chapter.

Alternating-current tests may be made with the apparatus shown diagrammatically in Fig. 10, in the *Transactions of the A.I.E.E.*, vol. 41, page 569, 1922, substituting the cable for the cell *C*.

The Weston microfarad meter gives equally good results on modern cables. It will read high if the lower factor is abnormally high.

For intermediate working voltages, the test voltage shall be interpolated.

Dielectric Loss.—Many cable users require dielectric loss tests either upon short lengths or full lengths of cable. Such tests are required only on paper-insulated cable for high voltages, say 7,500 volts or over.

The test is made by putting full working voltage on the cable and measuring the power furnished to it by means of a very delicate wattmeter, the conductors at the ends of the cable being spread apart and insulated to prevent leakage and corona.

The wattmeter must be specially compensated to correct errors arising from the low power factors to be measured. Compensation is effected by putting a condenser in series with the current coil of the wattmeter. This capacity may be adjusted further in accordance with the measured characteristics of the instrument or may be calibrated by testing with a zero-loss condenser and adjusting the compensating capacity until the reading of the wattmeter is zero. A diagram of connections is shown in Fig. 8.

Three-phase measurements, made as described by F. M. Farmer,[1] probably give the most satisfactory results for triplex cables, but very close agreement may be obtained by single-phase measurements, as follows:

Let $W_1 =$ loss at line voltage E with one conductor against the other two, the sheath being grounded.

$W_2 =$ loss at voltage $\frac{E}{\sqrt{3}}$ with all three conductors against sheath .

$W =$ total loss.

Then $W = 1.5\,W_1 + W_2$.

[1] *Trans. A.I.E.E.*, vol. 37, p. 221, 1918.

The measurement of such a small amount of power, at high voltage, and with current and voltage nearly 90 deg. out of phase, requires fine instruments and considerable skill in their use. Furthermore, the temperature must be kept constant at the value or values specified. In the United States, it is usual to put the cable in an air oven or oil bath.

European practice requires that the cable be heated for this test by passing current through the conductors. This practice has the advantage over the American method of more closely

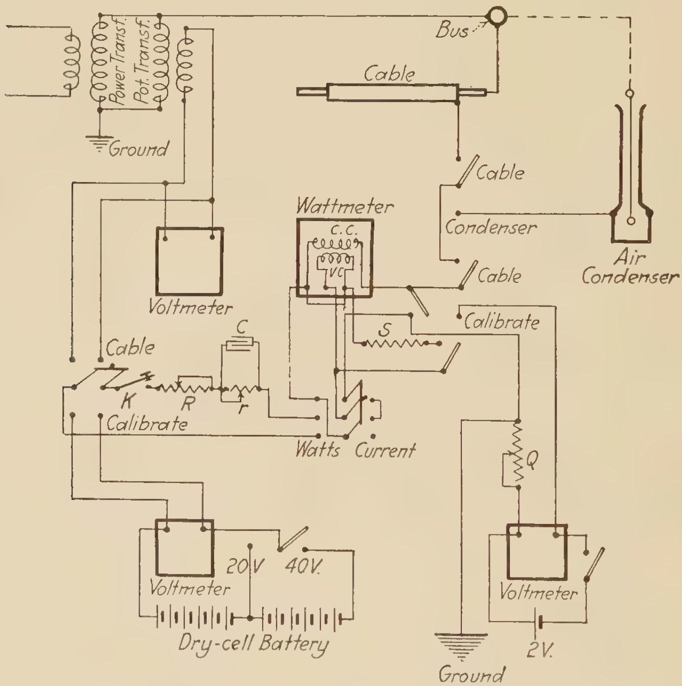

Fig. 8.—Dielectric-loss measurements. Diagram of connections.

simulating working conditions, but it is inexact, as the mean temperature of the insulation depends not only upon the conductor temperature, but also upon that of the surrounding air, which is liable to vary considerably.

Miscellaneous Measurements and Tests.—Lengths of small wire should be tested for continuity to make sure that the conductor is not broken. This is done by operating a bell or buzzer

through the wire, a broken wire being shown by the failure of the bell to ring.

A break may be located by measuring the capacitance of the wire from each end to the break. The ratio of the values of these capacitances equals the ratio of the distances of the break from the two ends.

Sometimes the resistance of the conductor must be measured. If the wire is long, the resistance is measured by a Wheatstone bridge.

Conductivity of unstranded copper is derived from resistance measurements, temperature and dimensions, using a bridge of special construction. Conductivity measurements are seldom made, as the conductivity of untinned copper is very uniform and averages 100 per cent of the Annealed Copper Standard.

The strands of crushed sector conductors are sometimes of irregular cross-sections, due to crushing after stranding. This condition makes it difficult to calculate the conductivity from resistance measurements, as it is not easy to obtain the mean cross-section of the numerous irregular strands.

The cable length, cross-section of conductor, thickness of insulation and thickness of lead sheath are the most important details to be checked.

TESTS AFTER INSTALLATION

Tests are made after installation and splicing either as acceptance tests or routine operating tests. The former are not always included in the purchase contract, and indeed the N.E.L.A. specifications require them only when the cable is installed by the manufacturer. When acceptance tests are made, they usually consist only of a high-tension test of not over 80 per cent of the factory-test voltage.

Routine tests are made at regular intervals in order to detect incipient faults and so prevent failures under load. The practice of different companies varies very widely, some companies making no high-voltage tests and others testing to 80 per cent of the factory-test voltage. Among those who make no high-voltage test, some make an insulation resistance test. If the insulation resistance is found to be abnormally low, a weak spot is to be suspected, and a high voltage is applied to break it down, if it will break down at a voltage not greater than 80 per cent of the factory-test voltage. It is claimed for this practice that it

prevents injury to the cables by eliminating frequent unnecessary tests at high voltage. It is well known, however, that insulation of low resistivity may be very strong dielectrically, and that of high resistivity may be very weak. Indeed, there is no connection between the two qualities except where moisture films exist, a negligible case in modern cables.

The best practice for testing high-voltage triplex cables with alternating currents is to use a three-phase transformer which will simultaneously test all phases against each other and against ground. Many companies, however, use a single-phase transformer with the central point of the high-tension winding grounded. When a given voltage is applied between conductors, the voltage from conductors to ground is about 14 per cent less than it would be with a three-phase equipment. As, however, three tests must be made in order to test the insulation between all conductors, the insulation to ground will be tested three times, so that the final effect may be as severe as in three-phase testing.

As the cable sheath is always grounded, the insulation between conductors and ground will be subjected to an indefinite voltage unless some part of the testing circuit is also grounded. This voltage may be much greater than that between conductors. In all this testing, it is, therefore, of the greatest importance that some part of the testing circuit be grounded.

The use of direct potential rather than alternating potential for high-voltage tests of installed cable is being investigated by operating companies. The larger size of the testing equipment which is required for alternating potential tests, because of the large charging current, makes it highly desirable to find a satisfactory d-c. method.

For several years d-c. cable-testing outfits have been made using a thermionic valve (kenotron) for rectifying purposes. This device is particularly valuable for testing long high-voltage transmission cables. For example, in order to test a 33-kv. transmission cable 14 mi. long at double voltage after installation, a transformer of about 2,500-kva. capacity is required. If a d-c. outfit is used for the purpose, the capacity can be reduced to about 5 or 10 kw. if the outfit is used only for making the high-voltage test. However, if it is to be used for reducing the fault after failure, so that the trouble can be located, it is necessary to be able to burn the insulation with the high-voltage

testing set, so that the resistance of the fault will be within the reach of the lower voltage fault-locating facilities available. This requirement may make it necessary to increase the capacity of the d-c. testing outfit to about 50 kw. Even in this latter case, however, the cost is only about one-quarter of the cost of the a-c. testing set.

The kenotron is a two-element vacuum tube containing a filament cathode supported within a cylindrical plate as anode.

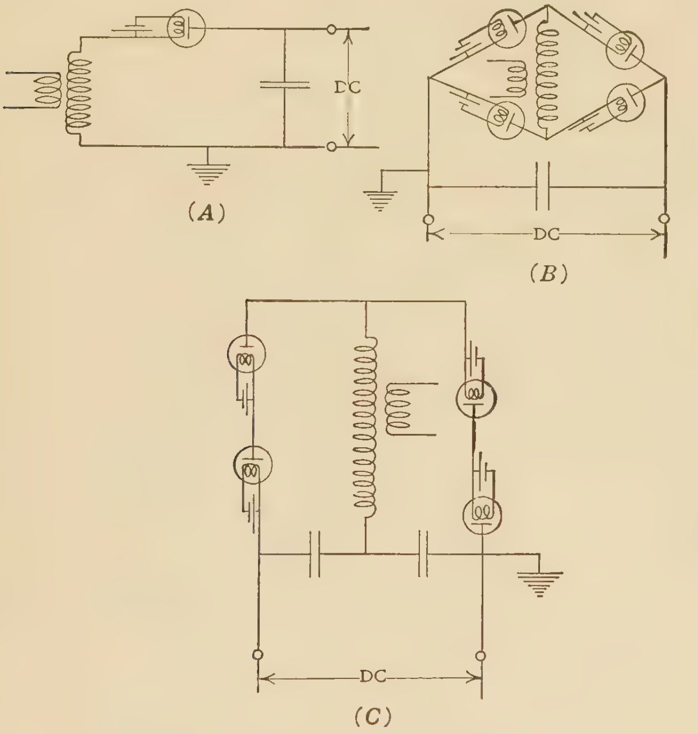

Fig. 9.—Kenotron rectifier connections.

The filament is kept incandescent by means of either a transformer or a storage battery. In operation, the kenotron acts simply as a unidirectional conductor, passing only the half waves of one polarity. Figure 9 shows some of the principal circuits used for kenotron rectification. Diagram *A* shows the simplest connection. The kenotron is in series with the supply transformer and a condenser storing the rectified voltage. This gives a direct current, as at every second half cycle the vacuum

becomes conducting. The principal advantage of such a connection is its simplicity, and, if the load is small compared with the condenser capacity, the voltage is quite steady. Diagram *B* shows the bridge type of connection. This has the advantage of passing through both half waves in such a way that they produce the same polarity on the receiving circuit. Diagram *C* shows the full-wave or double half-wave type, which has the principal advantage of requiring an alternating-voltage source of only approximately one-third the direct voltage. The purpose of the condenser is to smooth out the pulsations of the direct voltage. It is readily seen that the half-wave connection *A* requires more capacitance than a full-wave connection, either *B* or *C*. The capacitance required for satisfactory smoothing is dependent on the load. In testing long cables no capacitance additional to that of the cable is required, but laboratory tests on short lengths of cable or other test pieces of low electrostatic capacity necessitate the use of the condensers shown above. On account of the small direct current conducted by any type of insulation, the voltage fluctuation of such a rectifier can be reduced below 2 per cent without large condensers.[1]

An important matter in connection with the use of the kenotron set is the direct voltage which is equivalent to a given alternating voltage as far as its effect upon the insulation is concerned. The following discussion of this subject was contributed by the Standards Committee of the A.I.E.E. in the Institute's *Journal* of July, 1923, pages 757–758.

The ratio between the direct and root-mean-square alternating voltages which will produce failure of insulation depends upon:

1. The time of application of the voltage.
2. The nature of the insulation.
3. The temperature.
4. And possibly the thickness of insulation.

Considering only impregnated-paper insulation, and short-period applications of voltages, *i.e.*, periods so short that the average dielectric loss will not affect the dielectric strength, it is found that the ratio is 1.4 for fluid oil, somewhat higher, say 1.8, for impregnated paper at 100° C. and as high in some cables as 2.4 at 25° C.

The value of 2.4 for 25° C. is, however, apparently not a constant.

[1] Hayden and Eddy, A.I.E.E., 1923.

M. Weiset,[1] experimenting with a Delon rectifier, found a ratio of 2.46 for cable lengths of 100 m. or more, but obtained lower ratios for shorter lengths (1.7 to 1.8 for 3 m.).

Correspondence with M. Jules Delon, of Lyon, elicited the statement that the ratio, according to his tests, is 2.4.

Wallace S. Clark, writing under date of August 16, 1922, said:

> Tests made on cable manufactured by the General Electric Company, mineral base compound, showed, on single-conductor cables with 5-min. test duration, at 25° C., a ratio of 2.4 to 1; at 100° C. a ratio of 1.77 to 1 in.

Results obtained with commercial tests of cables on which, however, too much reliance should not be placed, indicate that the ratio depends upon the compactness of the paper fibers, *i.e.*, very compact paper immobilizes the oil in somewhat the same way as is done by lowering its temperature. This immobilization, which is probably ionic, as indicated in a paper by Del Mar and Hanson[2] seems to be a determining factor in the ratio.

As the compactness of the paper in old cables is quite unknown, it would seem unsafe to assume any ratio for such cables. On the other hand, the compactness of the paper is likely to differ in different makes of modern cables and there is danger of spoiling cables which would give excellent results with alternating current, if a direct voltage based on the ratio 2.4 is used in testing.

A paper by Phelps and Tanzer[3] indicates that the practical solution of this problem may possibly be found in applying a comparatively low direct voltage and observing the behavior of the insulation as revealed by its current-time characteristic. A manufacturer of electrical machinery has come to a similar conclusion with respect to machine insulation.

The subject is one which demands more experimental work, but such work would be very expensive because of the large number of cables which would have to be destroyed.

In the issue of the A.I.E.E. *Journal* containing the above report, Hayden and Eddy[4] give experimental data which show that the ratio increases with increasing rate of application of

[1] *E.T.Z.*, Jan. 15, 1920, p. 48.

[2] *Jour. A.I.E.E.*, June, 1922.

[3] *Jour. A.I.E.E.*, Mar., 1923.

[4] Dielectric Strength Ratio between Alternating and Direct Voltages.

the direct voltage. This is explained by Steinmetz in his paper on "Cable Charge and Discharge"[1] as due to the time occupied for the distribution of charges in a composite dielectric.

DETECTING FAULTS

Classification of Faults.—Faults, *i.e.*, insulation failures, may develop while the cable is in service, or in the course of a high-tension test. In the latter case, the fault is likely to have such a high resistance that it will be difficult to locate it by ordinary methods; it is, therefore, customary to "burn" the fault by passing current through it.

Cable faults may be classified as follows, with special reference to triplex cables:

A. Steady Conditions

1. Cable continuous	(*a*) Solid ground on one or two conductors. Third clear. (*b*) Solid ground on all three conductors. (*c*) Short circuit between two conductors. Third clear of ground. (*d*) Short circuit between two conductors. Third grounded. (*e*) Short circuit between all conductors and clear of ground.
2. Cable burned apart on one or more conductors	(*a*) to (*e*) inclusive as above from either end of cable.

B. Variable Conditions

1. Cable continuous	(*a*) Partial ground or grounds. (*b*) Partial short circuits.
2. Cable burned apart	(*a*) and (*b*) as above from either end of cable.

Preliminary Tests.—The first test should be for continuity. The usual method is to energize each conductor at 120 volts (direct current) to ground through a lamp, the far end of the cable being first grounded, and then having the grounds removed. The indications will be as follows:

Far End	Lamps Light	Lamps Out
Grounded	Continuous or grounded	Open leg
Not grounded	Grounded	Ungrounded

If the cable shows a grounded conductor, the test should be repeated, using a load resistance to bring the current to

[1] A.I.E.E., 1923.

10 amperes or more. If, under these conditions, the brightness of the lamp does not change as the ground at the far end is removed, the ground may be regarded as good. If one conductor is open-circuited, a ground on the far end may be tested by connecting one of the other conductors to it at the far end.

Direct current should be used for such tests, as with alternating current the capacity of the cable would allow the passage of sufficient current to keep the lamp bright under all conditions.

Methods of Test.—When the fault has been "burned" and its nature determined, it may be located either by tests made at one end or by successive tests along the cable. The former method can be used only when one or more unimpaired conductors are available, and in such cases it is usual to obtain an approximate location by tests at one end and, using this as a basis, to find the exact location by local tests. The tests made at one end are "loop tests," the principle of which is to determine the resistance of the cable conductor up to the fault as

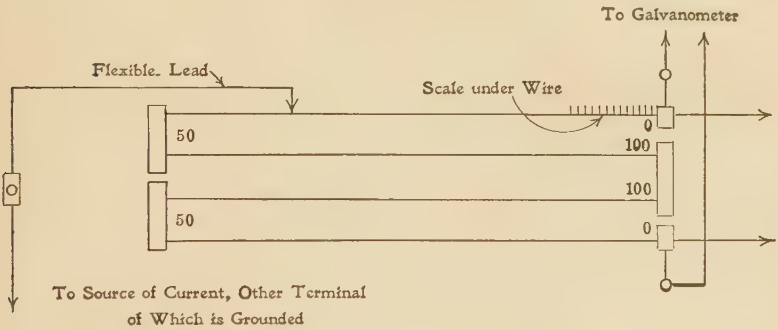

FIG. 10.—Murray loop test bridge.

compared with its total resistance, the distance of the fault being proportional to the resistance up to it.

The tests made along the cable are on the principle of passing a "tracing" current through the cable, which, due to some peculiar wave form, will produce a distinctive noise in a telephone. This noise is detected by means of a telephone connected to a portable coil laid on the cable successively at each splicing chamber. When a distinct falling off in the noise occurs between any two splicing chambers, it is an indication that the fault lies between them.

Loop Tests.—The bridge used in the Murray loop tests is shown diagrammatically in Fig. 10. This bridge may be used

for grounds or crosses. It consists essentially of a resistance wire graduated into two equal adjacent scales, each reading from zero at the outer ends to 100 at the point of junction. A galvanometer is connected across the ends and a flexible lead,

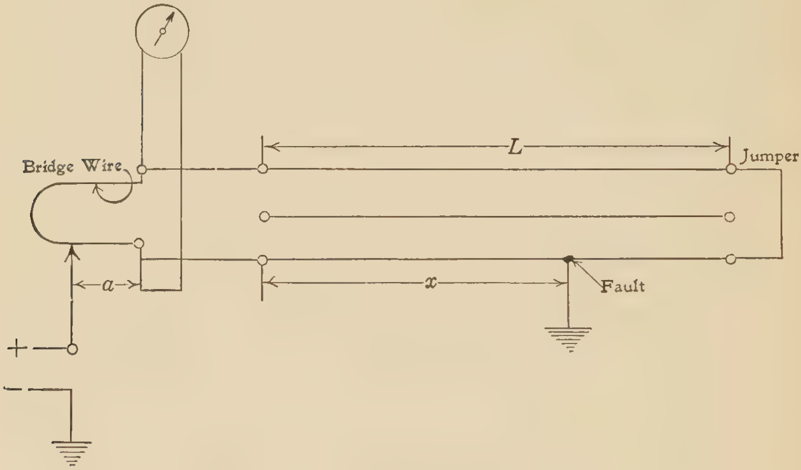

FIG. 11.—Murray loop test for ground.

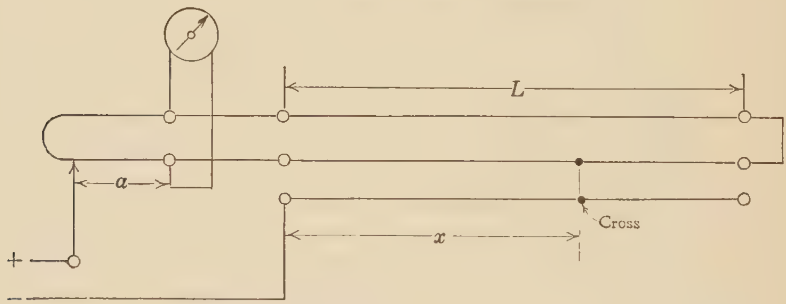

FIG. 12.—Murray loop test for cross.

connected to the positive terminal of a source of direct current, is put in sliding contact with the wire. The negative terminal of the current source is grounded. Connections are made as indicated below and the sliding contact moved until the galvanometer indicates zero.

Let L = length of cable.
a = distance of sliding contact, on bridge scale, to the terminal of the bridge connected to the faulty wire.
x = the distance from the bridge to the fault.

Then

$$x = \frac{aL}{100}.$$

For a ground, the bridge is connected as shown in Fig. 11, and for a cross as shown in Fig. 12, an extra unimpaired conductor being required in both cases and a jumper applied to the distant ends, as indicated.

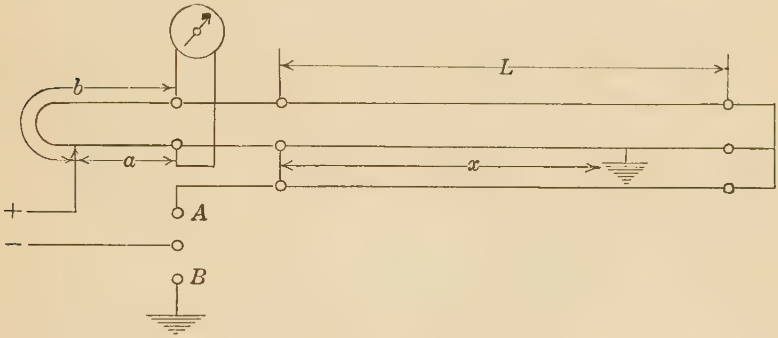

FIG. 13.—Fisher loop test for ground.

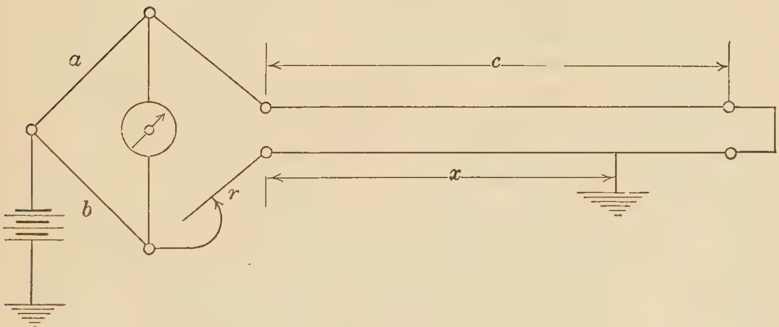

FIG. 14.—Varley loop test for ground.

Where two unimpaired conductors are available, the arrangement shown in Fig. 13, known as the Fisher loop test, may be used for detecting grounds, balance being obtained with switch at A and then at B. Let a and b then be the respective distances of sliding contact on the bridge scale to the terminal of the bridge contact connected to the faulty and the good wire. Then

$$x = \frac{a}{b}L.$$

The bridge used in the Varley loop test is shown diagrammatically in Fig. 14. It is available for either grounds or crosses. It consists essentially of two fixed resistances and one variable resistance arranged in bridge form, with the positive terminal of a source of direct current connected to the point of junction of the fixed resistances, and a galvanometer connected

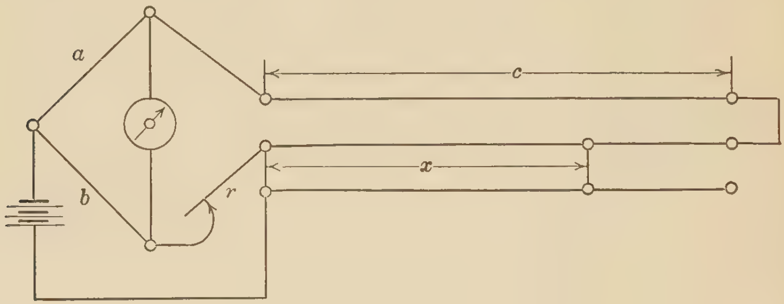

Fig. 15.—Varley loop test for cross.

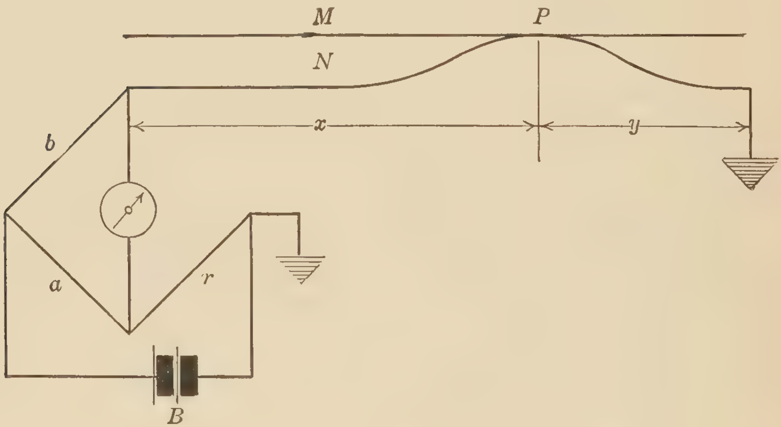

Fig. 16.—Ayrton and Mather loop test for cross.

across the outer terminals of the fixed resistances. Connections are made as indicated below and the variable resistance r varied until the galvanometer indicates zero.

Let c = resistance of unimpaired conductor.
a = resistance of bridge arm connected to unimpaired conductor.
b = resistance of bridge arm connected to grounded conductor.

Then, if x is the resistance from the bridge to the fault,

$$x = \frac{2bc - ar}{a + b}.$$

For a grounded conductor, the bridge is connected as shown in Fig. 14, and for cross-conductors, as shown in Fig. 15, an extra unimpaired conductor being required in both cases, and a jumper applied to the distant ends as indicated.

The Ayrton and Mather loop method bridge is similar to the Varley test, although available only for crosses, but two readings are taken, one with the connections shown in Fig. 16

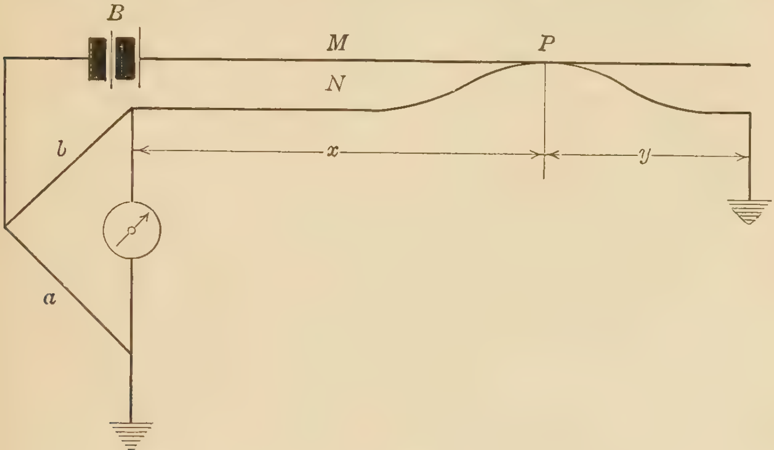

FIG. 17.—Ayrton and Mather loop test for cross.

and the other with the connections shown in Fig. 17. Let a, b and r be the bridge resistances when balance is obtained with the connections shown in Fig. 16 and a_1 the corresponding resistance when balance is obtained with the connections shown in Fig. 17. Then, if x is resistance from the bridge to the fault,

$$x = \frac{br}{b + a_1}.$$

No extra unimpaired conductor is required in this test.

It is important, in all loop testing, to use large testing leads and jumpers at both ends of the cable and to keep the contact resistances as low as possible. If the widely different results are obtained on reversal of the connecting leads, the results will be inaccurate.

Tracing Current Tests.—It is usual to start near the source of the tracing current and then go one-quarter of the length of the cable. If the indications are good at this point, the next test will be at the middle of the cable, and so on until the fault is located.

When there is only one conductor grounded and it is necessary to use the ground return for the tracing current, the listening coil will detect sheath currents and will, therefore, not give positive indications.

There are two ways to eliminate the sheath current: first, to "ring" the lead, *i.e.*, cut the sheath for about ½ in.; and, second, to short-circuit the sheath from end to end of the splicing chamber by means of a heavy copper shunt.

CHAPTER IX

CAPACITY, CHARGING CURRENT, POWER FACTOR

When alternating current is applied to a perfect condenser, the latter is charged as the voltage rises, and discharged as the voltage falls. The current is a maximum when the voltage falls to zero and a minimum when the voltage attains its crest value.

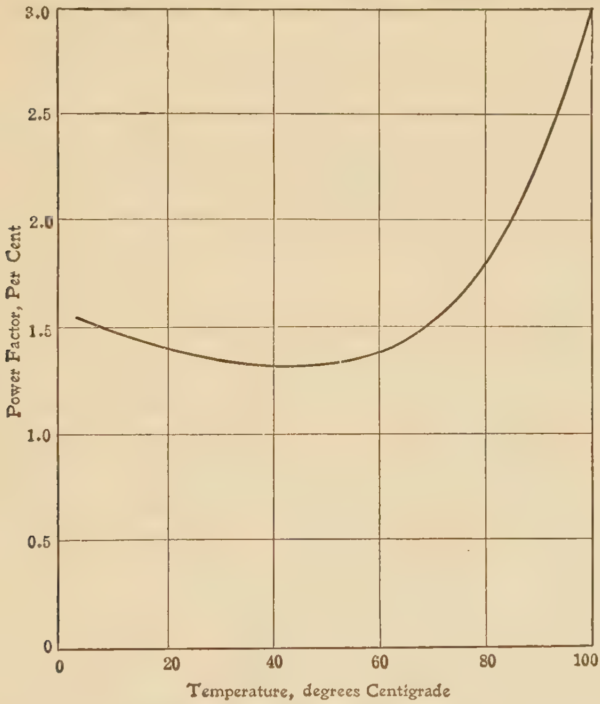

Fig. 18.—Power factor of a modern impregnated paper cable.

Hence, the current is always 90 deg. ahead of the voltage and their product, *i.e.*, the net power furnished to the condenser is always zero.

If, however, the condenser is more or less leaky, the current will lead the voltage by less than 90 deg., the difference between 90 deg. and the actual angles of lead being called the "imperfection angle."

The cosine of the angle of lead is called the "power factor" of the dielectric in the condenser. When the imperfection angle is zero, the angle of lead is 90 deg. and the cosine is zero. A typical curve showing the power factor of impregnated paper at various temperatures is given in Fig. 18.

The power furnished to the condenser and dissipated in its dielectric is the product of the voltage, current and power factor. This power is called the "dielectric loss" of the condenser.

Table V gives an idea of the values of these quantities for four typical cables, each of 500,000 cir. mils cross-section and with $^{40}\!/_{64}$ in. of insulation.

The exact nature of dielectric loss is not fully understood. It is known that it is not due merely to leakage current across the condenser.

There are three principal theories to account for its presence:

1. The Clerk-Maxwell theory of internal charges in a composite dielectric.
2. The Dubois theory of conducting moisture films.
3. The theory of dielectric hysteresis, the paternity of which is forgotten.

Table V.—500,000-cir. Mil Cable with $^{40}\!/_{64}$ In. of Insulation, Operated at 26,000 Volts

Quantity	30 Per cent hevea rubber insulation	Varnished-cambric insulation	Impregnated-paper cables made in 1920	Impregnated-paper cables made in 1923
Capacity, microfarad per mile	0.46	0.44	0.39	0.35
Specific capacity of insulation	4.8	4.5	4.0	3.5
Charging current, amperes per mile	4.5	4.3	3.8	3.4
Imperfection angle at 60° C.	27°	15°	5°	1°
Power-factor angle at 60° C.	63°	75°	85°	89°
Power factor at 60° C.	0.454	0.259	0.0871	0.0175
Dielectric loss, watts per foot at 60° C.	10.0	5.4	1.6	0.28
Heat dissipation, watts per foot	3.8[1]	3.7[1]	2.6	2.6

[1] The heat generated at 60° C. with 40° C. ambient temperature is greater than the heat dissipated, so that under these conditions rubber- or varnished-cambric-insulated cable would continuously rise in temperature merely by the application of voltage and without any current other than the charging current.

The first of these theories is the one most generally accepted at the present time, although it is only fair to say that it does not account for all the phenomena involved. The opportunity for research in this field is very great, and unusually interesting, not only because of the practical aspects of the problem but because it bears upon the fundamental ideas about the constitution of matter.

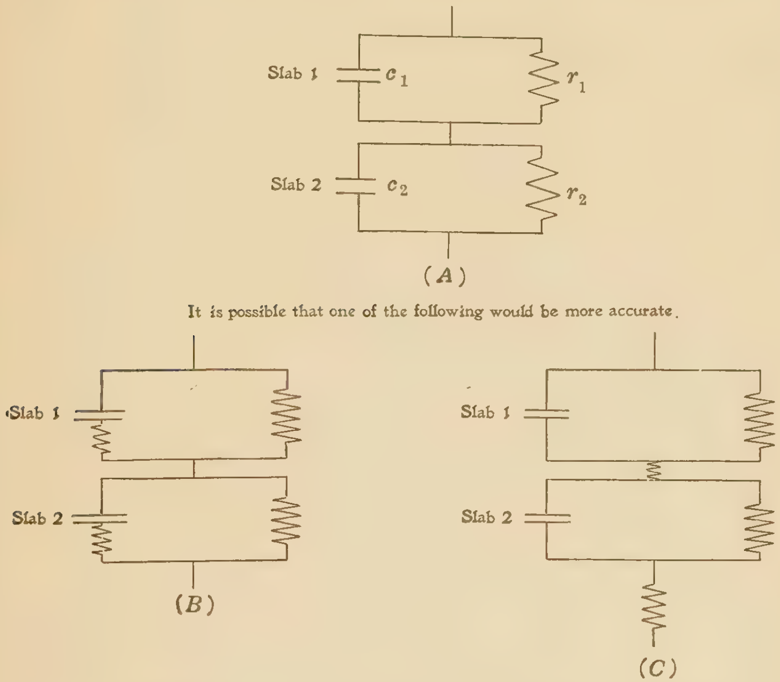

Fig. 19.—Representations of a dielectric as combinations of capacities and resistances.

Clerk-Maxwell assumed a dielectric composed of, say, two equal superimposed slabs of different materials having different values of resistivity and specific capacity. When a difference of potentials is applied between the outer surfaces of the composite slab, two tendencies manifest themselves. The leakage current through the slabs tends to distribute the potential drop across each slab in proportion to its resistivity; on the other hand, the condenser effect tends to distribute the potential drop across each slab in inverse proportion to its specific capacity.

The adjustment required to effect a compromise between these two tendencies involves a transfer of charges within the insulation from one slab to the other, and this transfer current causes ohmic loss, which is the dielectric loss.

If the specific capacities c_1 and c_2 are inversely as the resistivities r_1 and r_2, *i.e.*, if

$$\frac{c_1}{c_2} = \frac{r_2}{r_1},$$

the potential drops due to capacity will be in the same proportion as those due to resistance, and the dielectric loss due to the Clerk-Maxwell effect will be zero. The usual way of expressing this condition is to say that the products of the resistivity and specific capacity for each slab shall be equal, *i.e.*,

$$c_1 r_1 = c_2 r_2.$$

It cannot be denied that this Clerk-Maxwell effect takes place, but whether it is the principal cause of dielectric loss is not absolutely certain.

In order to study it quantitatively, it is necessary to express the characteristics of the composite dielectric in terms of resistances and capacities. The simplest representation is probably that shown in Fig. 19*A*. It is possible, however, that 19*B* or 19*C* may prove to be more accurate.

Impregnated-paper insulation consists of cellulose fibers and oil, the specific capacities of which are about 4 and 2 respectively. The resistivities depend greatly upon temperature and chemical composition. In 1922, Del Mar and Hanson applied the first circuit shown above to the case of impregnated-paper insulation, using for c_1, r_1, c_2, r_2 the specific capacities and resistivities of the cellulose fibers and oil. The practical results obtained seemed to justify the theory as far as they went, although the research was far from conclusive.

The above theory of dielectric loss may also be expressed in terms of the ionic theory.

The cellulose elements of impregnated paper are solid, whereas the oil elements may be shown experimentally to contain mobile ions of both polarities. When a difference of potentials is established inductively across a cellulose element, of greater magnitude than the ohmic drop across it, ions will be drawn to the surface of separation until the potentials are adjusted as explained above. With alternating current, the ions in the oil will be kept

in continual motion. Hence, the principal loss will occur in the oil and it can, therefore, be made a minimum by the use of oil of minimum ion mobility, *i.e.*, maximum resistivity.

The second theory of dielectric loss is that of Dr. D. Dubois, who believes that microscopic moisture films are responsible for

FIG. 20.—Drops of moisture elongating and short-circuiting the insulation.

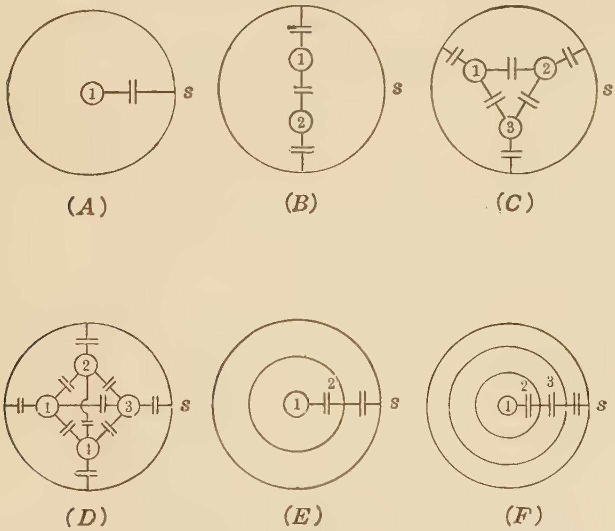

FIG. 21.—Equivalent capacities of various types of cables.

the trouble. These films are elongated by the electric field, due to their higher specific capacity, and thus bridge the dielectric, as shown in Fig. 20. The leakage current in these films causes an energy loss due to resistance, and this constitutes the dielectric loss.

The third theory is that of "dielectric hysteresis," *i.e.*, there is assumed to be some kind of molecular rotation at each cycle of voltage, which involves energy loss, such as is believed to occur in the alternate magnetization and demagnetization of iron. If there is any effect of this kind, it must be very slight, as indicated both by the comparatively small effect of frequency upon the dielectric loss of some composite dielectrics and by the fact that this effect depends greatly upon the sample of insulation tested.

The relation between the capacity of various combinations of conductors in a three-conductor cable is given in Tables VI and VII. The component capacities of various kinds of cable are shown in Fig. 21.

TABLE VI

Let a = capacity between one wire and the other two in parallel with the sheathing.

b = (a − ½ capacity between two wires in multiple and one wire and sheathing in multiple).

Capacity between one wire and the other two in parallel with the sheathing	$= a$
Capacity between two wires in multiple and one wire and sheathing in multiple	$= 2(a + b)$
Capacity between three wires in multiple and the sheathing	$= 3(a + 2b)$
Capacity between two wires	$= \frac{1}{2}(a - b)$
Capacity between one wire and two in multiple	$= \frac{2}{3}(a - b)$

TABLE VII

Let A = capacity between each conductor and the other conductors connected to the sheath.

B = capacity between individual conductors.

Capacity between one wire and the other two in parallel with the sheathing	$= A$
Capacity between two wires in multiple and one wire and sheathing in multiple	$= 4(A - B)$
Capacity between three wires in multiple and the sheathing	$= 3(3A - 4B)$
Capacity between two wires	$= B$
Capacity between one wire and two in multiple	$\frac{4}{3}B$

The capacity of a single-conductor cable may be calculated from the following formula in which:

C = capacity in microfarads per 1,000 ft.
K = specific capacity of insulation.
D = overall diameter of insulation.
d = inside diameter of insulation, *i.e.*, diameter of conductor.

$$C = \frac{7.354 \times 10^{-3} \times K}{\log_{10} \frac{D}{d}}$$

The capacity of a triplex sector cable is not so susceptible of calculation, due to the difficulty of expressing the sector contour mathematically.

The charging current of a triplex cable may be derived from the voltage between conductors E, if the capacity between each wire and the other two in multiple is known. This, as shown by Table VII, is four-thirds of B, the capacity between individual conductors.

Let I = charging current, amperes per conductor with sinusoidal e.m.f.

f = cycles per second.

C = capacity between each wire and the other two in multiple microfarads $= \frac{4}{3}B = \frac{2}{3}(a - b)$.

$$I = \sqrt{3}\pi fEC.$$

$$= \frac{5.44}{10^6} fEC.$$

The dielectric loss at 60 cycles may be calculated from the power factor and charging current, or from the power factor, capacity and voltage, as follows:

The power factor is independent of the voltage up to a certain point, and is independent of the shape and thickness of the insulation, within ordinary working limits. Hence, a table of power factors for different temperatures may be used to calculate the dielectric loss in any cable. The formulas are as follows:

Triplex Cables: $W = 0.143E^2KC \cos \Theta$.

Single-conductor Cables: $W = 0.0714E^2KC \cos \Theta$.

Where W = dielectric loss (watts per foot).

E = tension between conductors, triplex (kilovolts); tension between conductor and sheath, one conductor (kilovolts).

K = specific capacity.

= 3.5 cold to 4.0 hot, for impregnated paper.

C = capacity between two conductors, the third being insulated, assuming $K = 1$, triplex; capacity between conductor and sheath, assuming $K = 1$, one conductor (microfarad per mile).

$\cos \Theta$ = power factor.

TABLE VIII.—CAPACITY OF SINGLE-CONDUCTOR CABLES (SP. CAP. = 1)
C (Microfarad per mile)

Size, A. w. g. or circular inches	Insulation thickness—sixty-fourths of an inch						
	12	14	16	18	20	22	24
0	0.127	0.115	0.105	0.0943	0.0902	0.0853	0.0808
00	0.140	0.125	0.114	0.105	0.0980	0.0919	0.0886
000	0.152	0.136	0.124	0.113	0.106	0.0992	0.0936
0000	0.167	0.149	0.134	0.123	0.115	0.107	0.101
0.25	0.179	0.158	0.143	0.131	0.121	0.113	0.107
0.35	0.204	0.180	0.163	0.148	0.137	0.128	0.120
0.50	0.237	0.206	0.185	0.170	0.156	0.145	0.137
0.75	0.280	0.246	0.225	0.198	0.184	0.170	0.160
1.00	0.318	0.277	0.247	0.224	0.206	0.191	0.179

CHAPTER X

CARRYING CAPACITY OF CABLES

CURRENT AND TEMPERATURE RISE

The matter of carrying capacity, *i.e.*, the current or power which a cable can carry, is really the fundamental problem of cable engineering. Probably, the best way to obtain a clear conception of the problem is to consider the very simple physical relations involved.

Heat is generated in a cable, due to I^2R loss in the conductor, dielectric loss and eddy-current loss in the sheath. The heat generated in the conductor communicates itself to the insulation through which it must pass in order to escape and, together with the heat due to dielectric loss, reaches the sheath, where it joins the eddy-current loss, and is dissipated from the surface of the sheath into the ducts and finally into the earth.

If heat is generated more rapidly in the cable than it can be dissipated into the earth, the temperature of the cable will rise. If heat is dissipated at the same rate at which it is generated, the temperature will remain constant.

As the rate at which heat is dissipated from a body is approximately proportional to its temperature rise above the surrounding medium, a cable carrying a constant current will rise in temperature until the heat dissipated equals the heat generated, and constant temperature is therefore attained. The continuous carrying capacity of a cable is the current or power which causes a constant temperature equal to the maximum which the cable can safely stand.

This matter may be considered quantitatively.

Let I = current per conductor, amperes.

r = resistance of each conductor, ohms per centimeter.

W = dielectric loss in watts per centimeter of each conductor.

R = heat resistance from each conductor to earth, in degrees Centigrade rise per watt dissipated from a centimeter length of each conductor.

θ = temperature rise, degrees, centigrade, of conductor over earth temperature.

If it is assumed that the entire dielectric loss occurs in the insulation at the conductor surface, and if eddy-current losses in the sheath are neglected, both of which assumptions are ordinarily justifiable for practical calculations, the heat generated in and near the conductor may be equated with the heat flow from the conductor to ground. Thus

$$I^2r + W = \frac{\theta}{R}.$$

This gives the following formula for carrying capacity in amperes:

$$I = \sqrt{\frac{1}{r}\left(\frac{\theta}{R} - W\right)}.$$

Because of the approximation in regard to the location of the dielectric loss, this formula is conservative from an operating standpoint. For the same reason it is not quite fair as a basis for calculating bonuses or penalties for variations of dielectric loss from guarantees.

The heat resistance R from one conductor to ground in degrees Centigrade per watt lost in each centimeter of that conductor may be calculated from the following formulas:

Single-conductor Cables:

$$R = \frac{1}{\pi}\frac{H}{D_4} + \frac{2.302}{2\pi} K \log_{10} \frac{D_3}{D_2}.$$

(See below for explanation of symbols.)

Two-conductor Cables: The carrying capacity of two-conductor cables, either D-shaped or concentric, is substantially equal to that of a single-conductor cable of conductor area equal to that of the two conductors and insulated for the same voltage. Duplex (round) cables have about 5 per cent and twin (flat) cables about 15 per cent greater carrying capacity.

Triplex Cables:[1]

$$R = 3\left(\frac{1}{\pi}\frac{H}{D_4} + \frac{2.302}{2\pi} K \log_{10} \frac{D_3}{D}\right).$$

(This is the heat resistance of each conductor to air.)

Where D_1 = diameter of circle circumscribing the conductors, centimeters.

D_2 = diameter of each conductor, centimeters.

D_3 = inner diameter of lead sheath, centimeters.

[1] Mie, *Elektrotech., Zeit.*, vol. 26, p. 137, 1905.

D_4 = outer diameter of lead sheath, centimeters.

$$D = D_1 \sqrt[3]{\frac{3.06}{\frac{D_1}{D_2} + 2}}.$$

K = heat resistivity of the material of each layer of heat insulation in degrees centigrade rise per watt per centimeter cube (500 to 850).

H = heat resistivity from cable surface to room, in degrees centigrade per watt dissipated from each square centimeter of surface (1,100 for dull surface to 1,400 for bright surface).

The heat resistivity of impregnated paper varies over a range of at least 2 to 1. The Second Report on the Research on the Heating of Buried Cables[1] by the British Electrical and Allied Industries Research Association recommends that carrying capacities be calculated on the basis of the following heat resistivities:

For working voltages up to 2,200	$K = 750$
For working voltages above 2,200 and up to 11,000	$K = 550$

The latter figure is not confirmed by tests on American cables, for which a constant of $K = 1{,}000$ to $1{,}200$ is found safer, especially if used in connection with old cables.

The heat resistivity of the other common insulating materials are approximately as follows:

Rubber compound	$K = 725$
Varnished cambric	$K = 750$
Asphalted jute	$K = 250$
Impregnated cotton braid	$K = 750$

The heat resistivity from cable surface to atmosphere is as follows:

	H
Bright lead	1,400
Average lead	1,200
Dull lead	1,100
Impregnated cotton braid	775

The heat resistance of a duct line depends upon the number of ducts, their type, their depth below the surface and the heat resistivity of the soil. This last depends greatly upon the amount of moisture present. The heat resistance in degrees centigrade per

[1] *Jour., I.E.E.*, 1923.

watt-centimeter of duct varies between 25 and 50, a commonly used average (for 16 ducts) being 30.

The heat resistivity of soil is variable, as indicated by the following figures published by P. Torchio:

Dry sand	$K = 230$
Soil with 6 per cent moisture	$K = 100$
Soil with 18 per cent moisture	$K = 48$

TEMPERATURE LIMITATIONS

The preceding discussion takes no account of the reasons why it is necessary to limit the temperature rise in the cable. There are four reasons why cables cannot be allowed to rise indefinitely in temperature.

Longitudinal expansion leads to abrasive wear of the sheath and lateral expansion to stretching of the sheath. The former

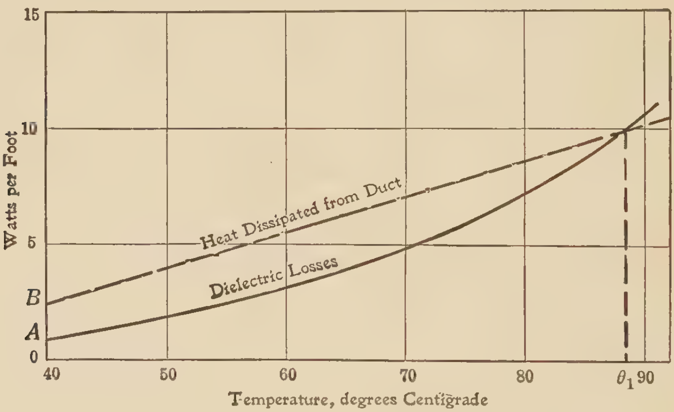

FIG. 22.—Heat generated and dissipated in an unloaded cable, assuming a ground temperature of 25° C.

phenomenon occurs principally at the edges of the ducts, where the cables frequently fail, due to the wearing through of the lead at these points. Lateral expansion is serious because lead is inelastic and the cooling of the cable is consequently accompanied by the loosening of the insulation from the lead. This creates voids between the paper and the sheath, which, as will be explained in the next chapter, cause weak spots.

The second limitation to the temperature at which a cable may be operated arises from the relation between dielectric loss and temperature. It was shown in the last chapter that the dielectric loss rises with the temperature and at high tempera-

tures the rise in dielectric loss becomes quite rapid. The dissipation of heat from a hot body such as a cable carrying current is, however, practically proportional to the temperature above the ambient medium. Thus in Fig. 22 the dielectric-loss curve will

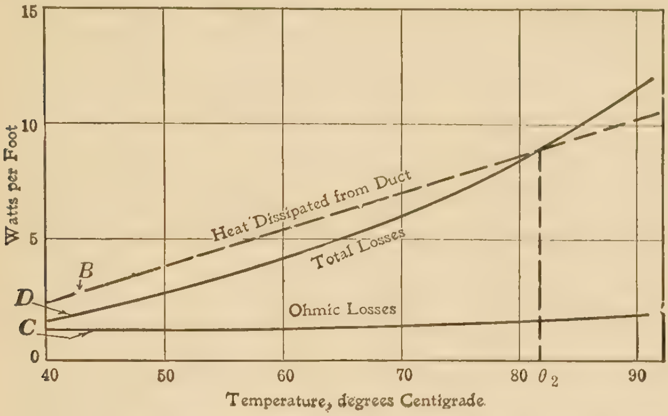

FIG. 23.—Heat generated and heat dissipated from a loaded cable.

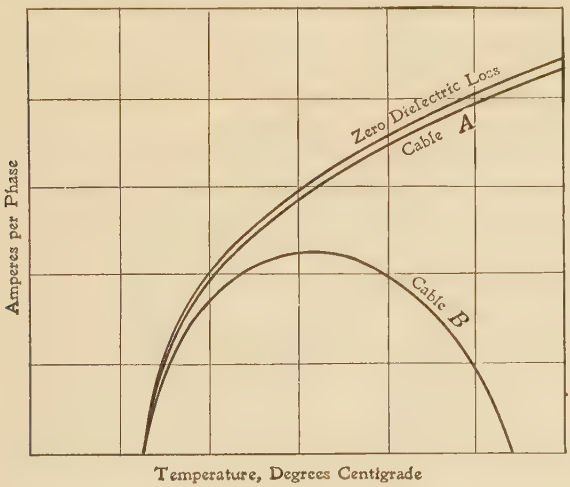

FIG. 24.—Carrying capacity of cables with different dielectric losses, when operated at various conductor temperatures.

have the form shown by curve A and the heat dissipation will have that shown by line B. It will be noted that, at a temperature Θ_1, the dielectric loss begins to exceed the heat-dissipating capacity of the cable.

Dielectric loss, however, is not the only energy loss in the cable. It must not be forgotten that when the conductor is carrying current there will be an I^2R loss in it. This loss will increase slightly with the temperature, due to the rise in resistance of the copper. For a given current, it will, therefore, have the form shown by the line C in Fig. 23. The total energy loss in a cable will, therefore, be represented by a curve which is the sum of A and C and is designated in Fig. 23 by the letter D. It will be noted that the curve D crosses the line B at the temperature Θ_2. If this temperature has been attained and the load on the cable is increased, the generation of heat in the cable will become greater than its ability to dissipate heat and the cable will, therefore, rise steadily in temperature until it burns out. This phenomenon is known as "cumulative heating" and is responsible for a large number of cable failures, especially on cables made prior to the year 1920.

Referring to the formula:

$$I = \sqrt{\frac{1}{r}\left(\frac{\Theta}{R} - W\right)}$$

since W is a function of temperature, there will be a value of W such that

$$W = \frac{\Theta}{R},$$

in which case I will be zero. Also, since W is a function of Θ, such that W increases more rapidly than Θ, there will be a value of W corresponding to a maximum value of the expression $\left(\frac{\Theta}{R} - W\right)$. Hence the curve between I and Θ will have the form shown in Fig. 24. The upper curve is based on $W = 0$, the middle one on a low value of W and the bottom one on a high value of W.

The third limitation of temperature in cables is the ability of men to work in the splicing chambers.

The fourth limitation of temperature is the temperature at which the insulation deteriorates, due to chemical decomposition.

When an impregnated-paper-insulated cable is heated, the order of resulting events is as follows:

The insulation begins to expand at once, the compound melts at about 55° C., the paper begins to lose its strength somewhere between 85 and 100° C. and chars at about 135 to 140° C. The temperature at which the compound begins to decompose depends on its nature, pure mineral oil remaining quite stable at

temperatures well above the charring point of paper. Compounds containing resin or resin oil are less stable. Simultaneously with the above effects, the resistivity of the compound drops rapidly, with consequent increase of dielectric loss.

The temperature of decomposition and combustion of the cable materials in air are as follows:

	Decomposition		Combustion	
	Degrees Centigrade	Degrees Fahrenheit	Degrees Centigrade	Degrees Fahrenheit
Paper, unimpregnated	140	290	275	480
Petrolatum	225	440	375	705
Rosin	145	300	335	635
Petrolatum (85 per cent[1]) and rosin (15 per cent)	175	350	325	627

[1] Slow decomposition of rosin compounds takes place below 100° C.

In the case of rubber insulation, the usual order of events is as follows:

Oxidation is accelerated if air is present; devulcanization commences, *i.e.*, the rubber molecule depolymerizes or breaks up, without, however, liberating any sulphur.

It has been found that exposure to air for 96 hr. at a temperature of 70° C. will make rubber compound deteriorate as much as it would at ordinary temperature in two years. Rubber decomposes at about 185° C. and burns in air at about 352° C.

In the case of varnished cambric, both the insulation resistance and the dielectric strength fall quite rapidly after the limiting temperature is attained. Varnished cambric decomposes at about 157° C. and burns at about 438° C. It becomes brittle at a temperature a little above 100° C., however.

Taking all these matters into account, the Standards Committee of the A.I.E.E. made the rule that impregnated paper should not be operated at a temperature over $(85 - E)°$ C., where E is the operating tension in kilovolts. This rule has been found to be fairly satisfactory for tensions up to about 25 kv., but the

opinion has been growing that for higher tensions no further temperature reduction is necessary, and that 60° C. is entirely satisfactory for tensions up to at least 35 kv. and probably higher.

The rule for varnished-cambric insulation is the same, except that 10° lower temperature is allowed because of the falling off in dielectric strength and the great increase of dielectric loss at temperatures higher than 75° C.

In the case of rubber insulation the A.I.E.E. rule allows $(60 - \frac{1}{4}E)°$ C.

In American practice, cables are laid in ducts where a number of other cables are in close proximity and have the effect of

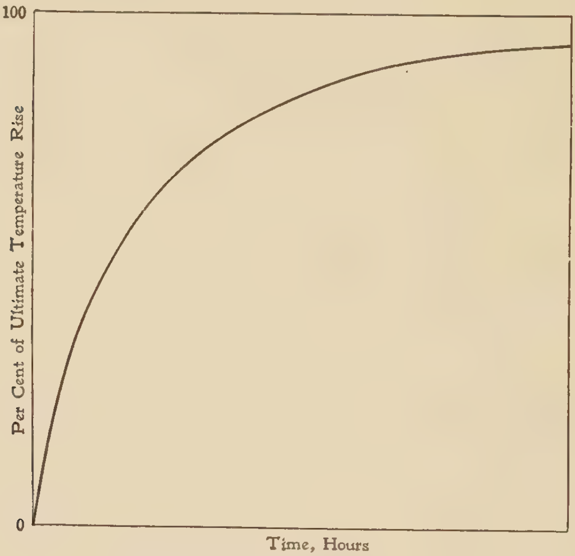

Fig. 25.—Temperature rise of cable.

raising the ambient temperature. It is usually assumed that an unloaded cable surrounded by loaded cables will have a temperature of about 40° C. Hence, temperature rises are calculated on the basis of an initial temperature of 40° C. and a final temperature in accordance with the A.I.E.E. rules named above.

Due to their thermal capacity, that is, their ability to store heat, cables may be operated for short periods with loads greater than normal. The rise in temperature of cable carrying current is of the form shown in Fig. 25. The slope of the tangent to

the curve at the point of origin indicates the thermal capacity of the cable. Very little study has been given to this subject. In general, it may be stated that power cables take about six hours to attain their final temperature and attain one-half of the final temperature rise in one hour. These figures are merely for the purpose of giving a general idea of the magnitudes involved, but of course the actual time is different for every cable, depending upon the amount of copper, insulation and lead used in its construction and upon the thermal capacity of the ducts or soil in which it is laid. Figure 26 shows the gradual temperature rise of the ducts, due to the presence of a cable in them.

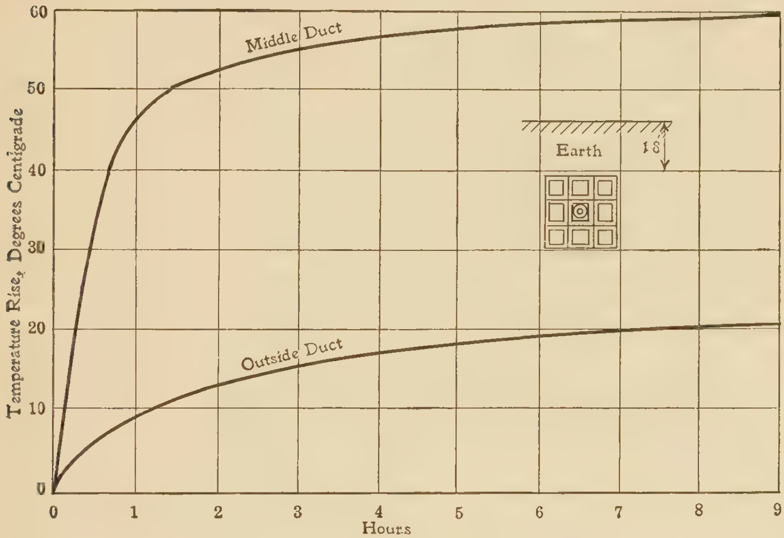

FIG. 26.—Temperature rise of ducts.

The short-period carrying capacity of cables is important to railway companies because of the short duration of their peak load. It is of very little interest to the lighting companies, as their peak loads usually last long enough to require the continuous carrying capacity of the cable.

Wires for house wiring have their permissible carrying capacities limited by the National Electric Code, as given in Table X. Several other tables of carrying capacities based upon the formulas given above are also included.

Table IX.—Maximum Continuous Carrying Capacities of Single-Conductor Cables in Open Air, Amperes

Assuming A.I.E.E. ultimate temperature and 40° C. air temperature
Single-conductor cables

Size	Rubber			Varnished cambric			Paper		
	Braid		Lead	Braid		Lead	Lead		
A .w. g. or circular	0 to 600 volts	7,000 volts	13,500 volts	0 to 600 volts	7,000 volts	13,500 volts	0 to 600 volts	7,000 volts	13,500 volts
14	20	...	...	...	...	...	30		
12	25	...	...	...	...	...	35		
10	30	...	...	...	...	...	50		
8	45	...	...	...	...	...	65		
6	60	60	55	75	75	60	85	75	65
4	85	80	70	105	100	80	120	100	90
2	110	110	100	140	130	110	160	140	120
1	130	130	115	165	160	130	185	160	140
0	155	150	130	190	185	150	215	180	165
00	180	180	160	225	210	180	250	220	195
000	210	205	180	265	255	205	290	250	225
0000	250	240	210	310	290	240	335	295	260
0.25	280	265	240	345	320	270	380	330	290
0.35	350	320	300	430	400	335	470	410	365
0.50	450	410	330	540	505	435	600	520	460
0.75	600	555	500	720	660	560	790	670	590
1.00	720	670	600	880	795	670	970	820	725

This table is based on the following resistivities:

Material	Degrees Centigrade per Watt per Cm. Cube	Degrees Centigrade per Watt per Inch Cube
Rubber	725	285
Varnished cambric	760	300
Impregnated paper	1205	475
Saturated braid	760	300

	Degrees Centigrade per Watt per Square Cemtimeter	Degrees Centigrade per Watt per Square Inch
Lead (to air)	1000	155
Braid (to air)	775	120

TABLE X.—CARRYING CAPACITIES, IN AMPERES, ALLOWED BY THE REGULATIONS OF THE NATIONAL BOARD OF FIRE UNDERWRITERS FOR INTERIOR COPPER CONDUCTORS

For aluminum 84 per cent of these currents is allowed

Single-conductor cables or each conductor of multiple-conductor cables

A. w. g.	Area, circular mils	Table *A*, rubber insulation	Table *B*, varnished cambric	Table *C*, other insulation
18	1,624	3	.....	5
16	2,583	6	.....	10
14	4,107	15	(18)	20
12	6,530	20	(25)	25
10	10,380	25	(30)	30
8	16,510	35	(40)	50
6	26,250	50	60	70
5	33,100	55	65	80
4	41,740	70	85	90
3	52,630	80	95	100
2	66,370	90	110	125
1	83,690	100	120	150
0	105,500	125	150	200
00	133,100	150	180	225
000	167,800	175	210	275
	200,000	200	240	300
0000	211,600	225	270	325
	250,000	250	300	350
	300,000	275	330	400
	400,000	325	390	500
	500,000	400	480	600
	600,000	450	540	680
	700 000	500	600	760
	800.000	550	660	840
	900.000	600	720	920
	1,000,000	650	780	1,000
	1,100.000	690	830	1,080
	1,200,000	730	880	1,150
	1,300,000	770	920	1,220
	1,400,000	810	970	1,290
	1,500,000	850	1,020	1,360
	1,600,000	890	1,070	1,430
	1,700,000	930	1,120	1,490
	1,800,000	970	1,160	1,550
	1,900,000	1,010	1,210	1,610
	2,000,000	1,050	1,260	1,670

Varnished cambric smaller than No. 6 may be used by special permission only.

Table XI.—Carrying Capacity of Three-conductor, Paper-lead Cables

Amperes per conductor

Size	Kilovolts, working pressure					
	7	11	15	19	22	27
6 A. w. g.	60.5	56.1	52.8	48.4	45.1	38.5
0	143.0	130.9	123.2	111.1	102.3	86.9
000	191.0	173.8	161.7	147.4	136.4	115.5
250,000 cir. mils	246.4	225.5	205.7	189.2	176.0	148.5
350,000	306.9	272.8	257.4	231.0	215.6	192.5
500,000	387.2	347.6	323.4	290.4	258.5	228.8
600,000	431.2	398.2	361.9	323.4	308.9	266.2

Based on an ambient temperature of 40° C. and the A.I.E.E. rule for maximum temperature. This ambient temperature is such as may be expected in a duct line containing many loaded cables.

Table XII.—Factor to Reduce Carrying Capacity per Cable When Several Equally Loaded Cables Fill a Duct Line

Number of ducts horizontally or vertically	Number of ducts vertically or horizontally							
	1	2	3	4	5	6	7	8
1	1	0.86	0.81	0.79	0.77	0.76	0.76	0.75
2	0.86	0.71	0.64	0.61	0.59	0.58	0.57	0.56
3	0.81	0.64	0.58	0.54	0.52	0.50	0.49	0.48
4	0.79	0.62	0.54	0.50	0.47	0.46	0.44	0.43
5	0.77	0.59	0.52	0.47	0.45	0.43	0.42	0.40
6	0.76	0.58	0.50	0.46	0.43	0.41	0.39	0.38
7	0.76	0.57	0.49	0.44	0.42	0.39	0.38	0.36
8	0.75	0.56	0.48	0.43	0.40	0.38	0.36	0.35

E.g., in a group of ducts 3 by 6 each of the 18 cables could carry only 0.5 of the current which could be carried by one cable alone. This table should be used only when the carrying capacity has been calculated on the basis of ground temperature as the ambient.

CHAPTER XI

DIELECTRIC STRENGTH AND INSULATION FAILURE

The subject of dielectric strength and insulation failure is occupying the attention of a great many minds, because of both its scientific interest and its commercial importance. Interest in the subject is by no means confined to cable engineers, but is of almost equal importance to transformer and insulator designers. Indeed, there is no single topic of electrophysics which can claim equal importance with it, as the future extension of electric power developments hinges upon the ability of insulating materials to keep pace with the demand for higher transmission voltages.

The practical aspects of the problem may be divided into two steps, as follows:

1. What condition or combination of conditions determine the breakdown of a dielectric?
2. Can this condition or combination of conditions be expressed in general terms which can be combined with dimensional data to express the breakdown voltage of a specific sample?

CONDITIONS WHICH DETERMINE THE BREAKDOWN OF A DIELECTRIC

Failure of a Dielectric.—The failure of a dielectric is the conversion of a part of it into a conductor, under the influence of electric stress. If the part converted makes a complete path through the dielectric, the failure is said to be complete. If, however, the part of the dielectric made conducting does not make a continuous path through it, the failure is said to be "partial."

It has been amply shown by Steinmetz and others that the breakdown of a dielectric requires the expenditure of energy. Energy involves electrical tension, current and time, so that the breakdown depends not merely on the applied voltage but is a complicated function of voltage, time and those characteristics which determine the current flow for a given voltage.

The conversion of a dielectric into a conductor involves either the mobilization of ions hitherto held bound, or the creation of new ions, or a combination of both actions.

Ions are mobilized by the electric stress, but the mobilization may become manifest as thermal, mechanical or chemical phenomena, so that dielectrics become conducting due, in the first place, to the electric stress, but more immediately to these secondary phenomena.

Thermal Failure.—It is a characteristic of dielectrics that they have a negative temperature coefficient of resistivity. Hence, if, due to some unevenness, one spot becomes hotter

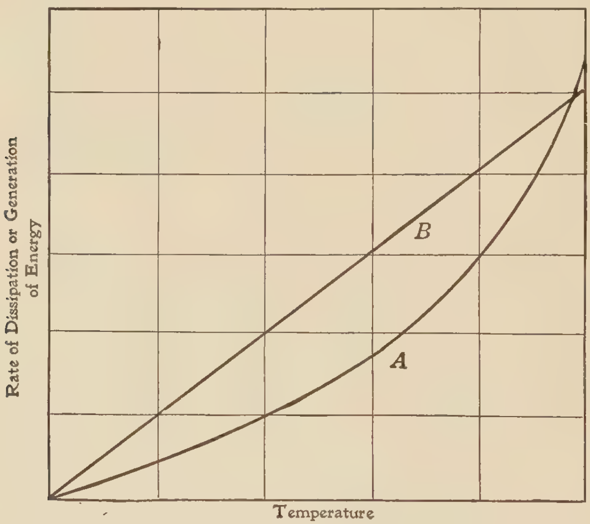

FIG. 27.—Relation between temperature and energy loss in a filament of insulation.

than another, the resistivity of the hot spot will decrease, and it will receive more energy than the cooler ones, with the result that the temperature difference further increases. There is thus a certain relation between the temperature of a heated filament of insulation and the energy loss in it, which may be represented as a curve, such as *A* in Fig. 27. There is also a relation between the temperature and the heat energy which is dissipated from the filament, such as *B* in Fig. 27. As long as curve *A* is under curve *B*, only local and limited heating of the filament can occur. But if such a temperature is reached that

curve A crosses curve B, the temperature will rise cumulatively, because heat is being generated faster than it can be dissipated.

It follows from this that, if the voltage across a dielectric be gradually increased, the current at first will rise proportionately with the voltage, but, as hot spots develop, the current will rise faster than the voltage, until the I^2R loss at some spot exceeds the heat-dissipating power, when cumulative heating will occur and the current will continue rising without any further rise of

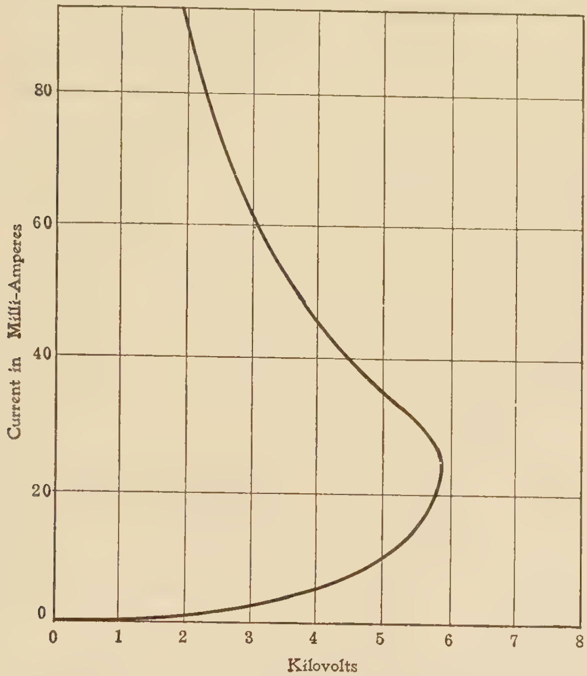

FIG. 28.—Volt-ampere characteristic of impregnated paper of 0.0217 cm., thick and 2.3 cm. square tested with mosaic electrodes.

voltage. Indeed, due to the destruction of part of the dielectric, the current will continue to rise even if the voltage is lowered. Consequently, the volt-ampere characteristic of a dielectric will have the form shown in Fig. 28.

Such characteristic curves have been plotted by K. W. Wagner for glass, mica, cellon, gutta percha, vulcanized rubber and impregnated paper, using mosaic electrodes, *i.e.*, those which conduct in one direction only, to ensure that only the current

involved in the failure will be measured and none will come laterally from other parts of the condenser. Figure 28 is from tests on impregnated paper, and the breakdown voltage corresponds to a stress of about 268 kv. per centimeter (maximum), but it is clear that, once cumulative heating has started, it will progress with as low a stress as 92 kv. per centimeter.

The question at once arises—What is the original nature of the spot which develops into a hot spot? Undoubtedly the cause varies for different materials, but in impregnated paper it appears to be generally the presence of an air or vapor pocket. Air or vapor is a poor conductor of heat; hence, if the heat escaping from the insulation encounters a vapor pocket, it will be held back and deflected, with consequent abnormal rise of temperature in the insulation behind the vapor pocket.

The presence of a vapor pocket promotes local heating in another way, which may be more important than the one just cited. Air has a specific capacity between one-third and one-quarter that of impregnated paper. Hence, if a large film of air is present, the principle of condensers in series comes into play, and the potential gradient in the air will be between three and four times that in the impregnated paper. Air, however, has a comparatively low dielectric strength, so that when the stress in the insulation reaches one-third to one-quarter of the dielectric strength of air, the air pockets becomes ionized, causing a great increase in the surface leakage and discharges along the surfaces of the paper, which burns in fern-like patterns.

Disruptive Failure.—The disruptive failure of dielectrics is not well understood, but explosive actions under high stress are well known, where no direct evidences of heat exist.

Chemical Failure.—Failure by the conversion of a dielectric into a partial conductor by chemical transformation is not uncommon.

Thus, rubber insulation under high stress is oxidized in the presence of air, due to the formation of ozone, which has a rapid destructive effect on rubber. The failure of rubber insulation is generally due to this action, if it cannot be traced to foreign particles or air bubbles which would create local hot spots.

Impregnated-paper insulation is now known to undergo injurious chemical changes under stress. There is a little-understood action whereby the oil becomes hard and sometimes acquires a strong and unpleasant odor. This is believed by some

to intensify the surface discharges between tapes and eventually lead to failure.

Electric Field Intensity or Potential Gradient.—The intensity of an electric field may be expressed in either of the following units:

Abvolts per centimeter.
Statvolts per centimeter.
Kilovolts per inch.
Volts per $\frac{1}{64}$ in.
Volts per mil.
Kilovolts per centimeter.

The last volt is most commonly used in cable and insulation problems and has the following relation to the others:

1 kv. per centimeter = 10 abvolt per centimeter.
= 3.33 statvolt per centimeter.
= 2.54 kilovolts per inch.
= 39.7 volts per $\frac{1}{64}$ in.
= 2.54 volts per mil.

The electric strength of insulation is measured in terms of the field intensity or potential gradient which causes failure. It is not a constant quantity for a given material, but varies with a number of circumstances. Nor must it be assumed that, because of these relations between the units, the dielectric strength is independent of the insulation thickness. The potential gradient is to be conceived of as a differential,

$$\frac{dV}{dL}$$

where L is an infinitesimal thickness across which the potential drop V occurs.

Breakdown of Air.—The simplest case of insulation failure, and the one most thoroughly investigated, is that of air and other gases.

Ordinarily, a gas is a very poor conductor of electricity. If, however, the gas is ionized, *i.e.*, if the molecules are given charges, the gas will become more or less conducting. If the ions travel at sufficient speed, new ions will be generated by collision with neutral molecules. Thus, if a potential gradient be established in a gas by means of a pair of charged electrodes, the gas near the electrodes will be ionized by collision with them, and will be set in motion. If the gradient is sufficient, they will

ionize other molecules by collision, which, in turn, will produce new ions. The positive ions will travel to the negative electrode and the negative ions to the positive electrode, which is another way of saying that the gas has become conducting.

If the potential gradient is great enough to create the requisite store of energy in the moving ions, sparkover will occur, *i.e.*, the dielectric will fail.

In the radial electric field around a wire, the field intensity is greatest at the surface of the conductor, so that, if this intensity is just equal to the rupturing gradient, the intensity at an infinitely small distance from the conductor surface will still be below the rupturing gradient. Hence, in order to accumulate the amount of energy necessary to cause rupture, the gradient at the conductor surface must be increased so that, at a finite distance away, the gradient will be that necessary for rupture. It has been found experimentally that this finite distance is a function of the conductor radius and equal to $0.301\sqrt{r}$ cm. At this distance from the conductor, the gradient at rupture is always constant for a given air density, the value being 30 kv. per centimeter maximum or 21 kv. per centimeter effective, on a sine wave.

The relation between the maximum stress at failure g_v, the dielectric strength g_o and the conductor radius may be expressed by the equation

$$
\begin{aligned}
g_v &= g_o\left(1 + \frac{0.301}{\sqrt{r}}\right). \\
&= 30\left(1 + \frac{0.301}{\sqrt{r}}\right) \text{ kv. per centimeter maximum.} \\
&= 21\left(1 + \frac{0.301}{\sqrt{r}}\right) \text{ kv. per centimeter effective.}
\end{aligned}
$$

If the air is in the form of thin films, the mean free path will be restricted and a greater potential gradient will be required to accelerate the ions to ionizing velocity. Thus the following values for the dielectric strength of thin air films were obtained by Dubsky:

Thickness of air film, centimeter	Electric strength of films, kilovolts per centimeter, 60 cycles	
	Maximum	Effective
0.0051	101.0	71.5
0.0122	96.5	68.3
0.0260	58.5	41.4
0.0560	53.0	37.5
0.120	42.4	30.0
0.275	37.3	26.4
0.455	35.1	24.9
	30.0	21.2

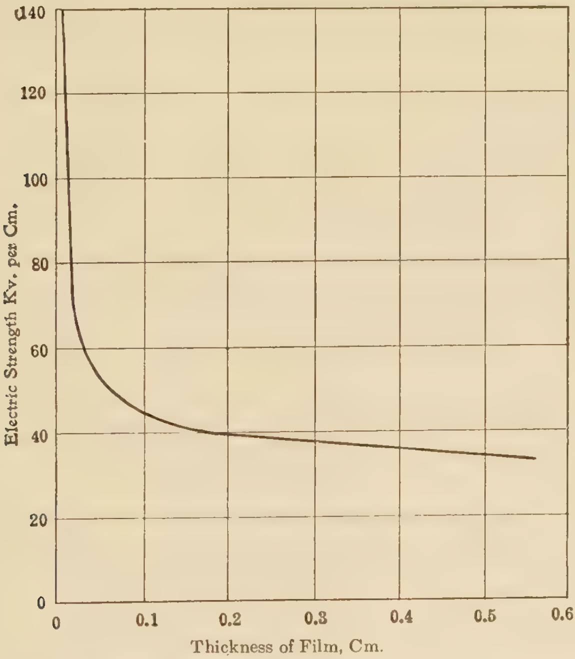

Fig. 29.—Electric strength of air films of various thicknesses.

These values are plotted as Fig. 29.

Thin gas films are of interest in the study of failure in solid dielectrics because of the frequent presence of entrapped air. If a film is thin compared to its area, it will not greatly deflect

the field, and consequently the same lines of electric force will pass through it as through the adjacent solid dielectric. The same applies to thick films of air concentric with the insulation, as in the case of an insulated conductor concentrically placed in a large metallic pipe. The potential drop in the film will be K times that in the contiguous solid, since the specific capacity of the solid is K times that of air, K always being greater than unity.

Thus, in the case of impregnated-paper insulation, with a specific capacity of about 3.5, the electric strength will be attained with the following effective gradients *in the impregnated paper:*

Thickness of Air Film, Centimeter	Gradient in Impregnated Paper to Produce Corona in Air Film, Kilovolts per Centimeter Effective
0.0051	20.4
0.0122	19.5
0.0260	13.0
0.560	11.8
0.120	8.6
0.275	7.5
0.455	7.1
∞	6.0

The thinner films are liable to occur inside of cables, so that air ionization may occur when the gradient in the insulation approaches 19 or 20 kv. per centimeter.

The case of the thicker films will be considered in the next chapter, as it presents some very special features; but it is of interest to note the very low gradient in the solid insulation, which will produce ionization in a contiguous thick air film.

Breakdown of Oils.—The behavior of oils under electric stress is very similar to that of gases, *i.e.*, the ionic theory applies and the formula for breakdown is of the same form. Thus

$$g_v = g_o\left(1 + \frac{1.2}{\sqrt{r}}\right)$$

where for dry transformer oil $g_o = 36$ kv. per centimeter maximum, or 25.5 kv. per centimeter effective, with sine wave.

Petrolatum has the same order of electric strength.

It is of interest to note that the energy distance $(= 1.2\sqrt{r})$ is about four times that of air, indicating a greater number of collisions necessary before ionic saturation is reached.

If the free path of the oil is broken up by barriers, such as paper fibers, the dielectric strength will be multiplied by about

four to six. Hence, the effective dielectric strength of oil-impregnated paper, in cables, is found to be from 100 to 150 kv. per centimeter.

The behavior of oil under electric stress, however, is very erratic. Successive observations of its disruptive voltage, made by Hayden and Eddy, under the most carefully controlled conditions, differed by a percentage many times greater than the accuracy of the test, the minimum being as low as 49 per cent of the average.

Breakdown of Solids.—The breakdown of solid dielectrics is but little understood, except that at ordinary frequencies and with gradual application of voltage failure generally results from hot spots. With high frequencies, or with sudden applications of high voltage, solid dielectrics are liable to be suddenly perforated with minute holes like pinholes, which often show no signs of charring at their edges.

The nature of this failure is not understood, and presents a splendid field for research, as the experimental work can be done with currents of such high frequency as to be harmless to the experimenter, who is thus able to observe the phenomena from close range.

Using mosaic electrodes as previously described and making them of material of low heat conductivity, so that the escape of heat from hot spots was parallel to the faces of the electrodes, Wagner found the dielectric strength of solid insulation to be independent of its thickness, *i.e.*, the breakdown voltage is proportional to the thickness.

On the other hand, Steinmetz has shown that if all the heat escapes from the hot spots toward the electrodes, the breakdown voltage will be proportional to the square root of the thickness.

The element of time is of especial importance in the failure of solid dielectrics. Wagner found the relation between time and breakdown voltage to follow a curve such as is shown in Fig. 30. This curve is of universal application if the scale of the abscissas be made to depend upon the ratio of thermal conductivity to thermal capacity of the material, which, in turn, depends upon the materials and dimensions of both the dielectric and the electrodes.

Peek gave another relation between breakdown stress and time.

Let T = time of application, seconds.

g = dielectric strength corresponding to time T, kilovolts per centimeter.

g_s = gradient that insulation will stand for an infinite time.

a = factor depending upon the thickness of insulation, temperature, etc.

Then
$$\frac{g}{g_s} = 1 + \frac{a}{\sqrt[4]{t}}.$$

He says that the equation generally applies well over a range from infinite time to 0.01 sec., but that for shorter periods many

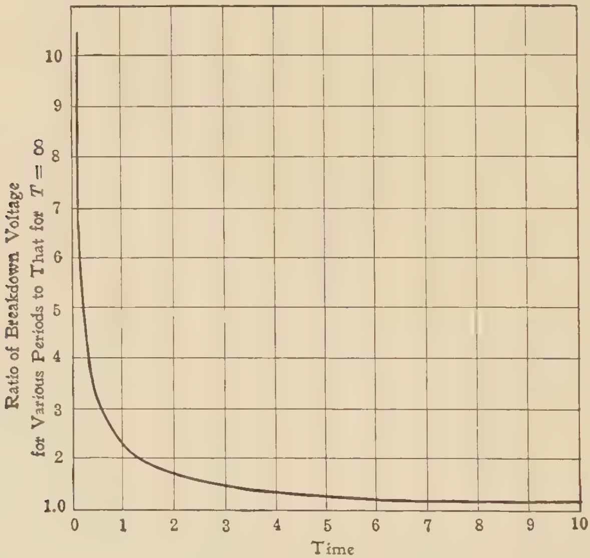

FIG. 30.—Relation between time and electric strength, according to K. W. Wagner's theory.

kinds of insulations fail at voltages lower than the equation indicates.

V. M. Montsinger, *Journal, A.I.E.E.*, February, 1924, gives the following modication of the above formula:

$$R_E = b + \frac{1 - b}{\sqrt[4]{T}}.$$

Where R_E = the ratio of breakdown voltage for T min. to that for 1 min.

b = experimental constant having values 0.85 for flat sheets of impregnated paper and 0.675 for varnished cambric.

Experiments on impregnated-paper cables by C. F. Hanson indicate a value of 0.42 for the constant, but Mr. Hanson's equation gives the ratio of breakdown voltage for T min. to that for 30 sec. or less. A graph of the latter equation is given in Fig. 31.

It was explained in the chapter on Dielectric Loss, that the electrical properties of a laminated dielectric depend upon the relative resistivities and specific capacities of adjacent lamina, and dielectric loss was explained as being, in large measure, the ohmic loss due to internal readjustment currents.

How the same properties affect the dielectric strength will now be considered. For simplicity, assume two superimposed

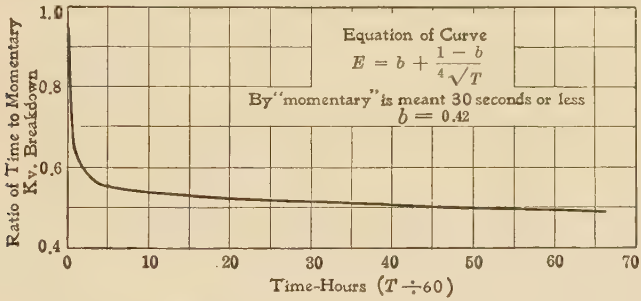

FIG. 31.—Relation between time and electric strength of impregnated paper, according to tests by C. F. Hanson.

layers of dielectric between the plates of a condenser, the two layers differing in specific capacity and resistivity.

If a difference of potentials be applied across the condenser, the potential gradients will initially be inversely as the specific capacities, but eventually will be proportional to the resistivities, because the internal leakage will neutralize the originally different charges on the two layers.

If therefore, a potential difference be applied for a short time, and then the condenser left open-circuited, the difference of potentials across the condenser will drop to zero at the instant of open-circuiting and then, due to the residual charges, will rise again, but this time the gradients will be proportional to the resistivities.

If a potential difference be now applied, of opposite polarity, it will add itself to that due to the residual charge.

If the layer of low specific capacity also has higher resistivity, the resultant gradient on that layer may be very high.

In the case of impregnated paper, where it is necessary to deal with layers of cellulose and of oil, the oil has both the lower specific capacity and the higher resistivity, especially in the case of low power factor cables, and is, therefore, peculiarly sensitive to this action.

The effect of frequency upon the time required to break down transformer insulation, according to F. J. Vogel, is given in Table

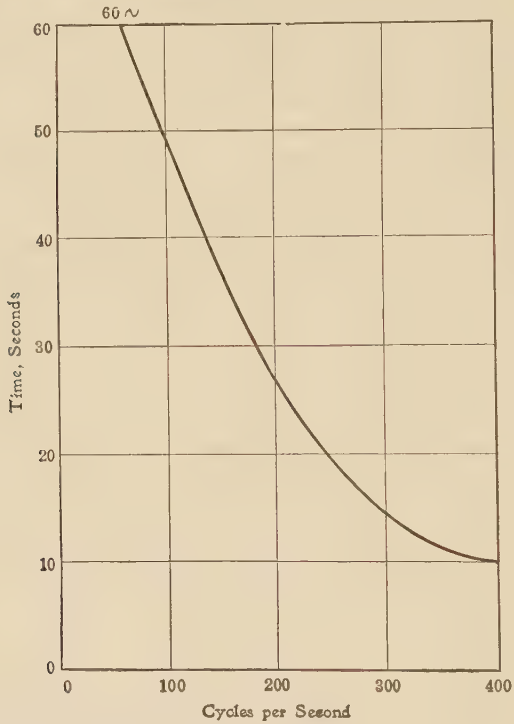

FIG. 32.—Effect of frequency upon time required to rupture transformer insulation.

XIII, a graph of which is shown in Fig. 32. Similar data are not yet available for cable insulation.

Thus far only the conditions which determine the breakdown of dielectrics have been considered. The chapter after the next will treat more fully the question of how these conditions may be applied to the determination of the breakdown voltages of specific cables. But in the meanwhile there will be a chapter on a subject which cannot be neglected in a study of insulation failure, namely, that of transient phenomena.

TABLE XIII.—EQUIVALENT VOLTAGE TESTS AT VARIOUS FREQUENCIES

(F. J. Vogel, *Trans. A.I.E.E.*, 1924)

Frequency, Cycles	Time, Seconds
60	60
120	44
164	33
208	26
240	21
360	11
400	10

CHAPTER XII

WAVES AND SURGES IN CABLES

CABLES AS RESERVOIRS OF ENERGY

Electric wires and cables are often thought of as simply carriers of electric energy, but serious trouble may occur if the fact is neglected that they are also reservoirs of energy. Under some conditions the stored energy may become destructive of both conductors and insulation.

It should be stated at the beginning that the subject is one which, in principle at least, is susceptible of mathematical treatment, but that actual conditions are usually so complicated that mathematical analysis is well-nigh impracticable. There are several treatises on the subject which attempt mathematical treatments, but, as a rule, they neglect very important factors and reach conclusions which are seriously at variance with observed facts.

The subject is obviously too big to cover adequately in a single chapter, so that it has seemed advisable to avoid mathematics and to give only those quantitative relations which are of a fundamental character. This will make it possible to obtain a general, if somewhat superficial, view of the subject, which, however, should be of assistance in correlating the general theory with practice. It has been found, in practice, that quantitative studies are useful for ascertaining possibilities rather than for determining actualities.

It was shown by J. H. Poynting[1] that the flow of energy in an electromagnetic field is in a direction at right angles both to the electric field and the magnetic field and that the flow of energy across any surface is proportional to the product of the electric and magnetic field intensities and the sine of angle between them.

An electromagnetic wave is a flow of energy by the agency of a combined magnetic and electric field, the two fields traveling together and mutually sustaining each other.

The flow of energy along a cable is by electromagnetic waves.

[1] *Phil. Trans.* vol. 75–2, p. 343, 1884.

Every transmission line consists of elements having capacity, inductance, resistance and dielectric loss.

When an e.m.f. is applied, energy is stored:

1. As electric charges by virtue of the capacity.
2. As magnetic energy by virtue of the inductance.

During the transfer, however, some of the energy is dissipated.

1. In the copper, by virtue of its resistance.
2. In the dielectric, by virtue of its power factor.

When an e.m.f. is applied to a cable, energy storage commences with a rush, and continues at a decreasing rate until the electric charge and the magnetic field have attained their maximum values, which are, respectively,

$\frac{1}{2}CE^2$, where E is the maximum instantaneous value of the voltage, and

$\frac{1}{2}LI^2$, where I is the maximum instantaneous value of the current.

The transmission line may be considered as made up of a number of sections, some long, others short, in each of which the capacity, inductance, resistance and dielectric loss are uniform per unit of length. The junction of two sections may be called a transition point, because at every such junction there is a change of value of one or more of the four quantities enumerated.

Dielectric loss is equivalent in its effect to leakage conductance or leakance. Thus, in a short piece of cable, in which the dielectric loss is assumed to be purely ohmic, if the leakage resistance is r_1 the power loss will be $\frac{E^2}{r_1}$. In another cable in which the dielectric loss is not necessarily ohmic, but can be expressed by means of a power factor K, the power loss will be $EIK = \omega E^2CK$, where C is the capacity; hence the two cables will show the same dielectric loss if

$$\frac{E^2}{r_1} = \omega E^2CK, \text{ or } \frac{1}{r_1} = \omega CK.$$

But the leakage conductance or leakance $g = \frac{1}{r_1}$; therefore

$$g = \omega CK.$$

Hence each section of line may be described in terms of four constants, r, L, C and g.

The energy stored electrically in a wave length of line is always equal to that stored magnetically, that is,

$\frac{1}{2}CE^2 = \frac{1}{2}LI^2$, where C and L relate to wave lengths.

Hence $\frac{E}{I} = \sqrt{\frac{L}{C}}$, and this ratio is called the "surge impedance." Its reciprocal is called the "surge admittance." Since L and C refer to the same length of line, the surge impedance is only a function of the L and C per unit of length.

Having thus made clear the fundamental circuit constants, the next step will be to consider what happens in a circuit to which an e.m.f. is applied.

ALTERNATING-CURRENT EFFECTS

Present-day transmission systems are concerned with alternating currents, usually in three phases. When an alternating e.m.f. E is applied to one end of such a system, the potential of the whole line does not suddenly become E, but, on the contrary, the distant points will at first have no potential. The potential, however, travels at a speed of several thousand miles per second. The actual value in miles per second is given by the following formula:

$$v = \frac{\omega}{\beta}.$$

Where

$$\beta = \frac{10^{-3}}{\sqrt{\frac{1}{2}(yz + bx - gr)}}$$

and

$r =$ conductor resistance, ohm per mile, taking into account the skin effect.

$x =$ conductor reactance, ohms per mile.
$\quad = \omega L.$

$z =$ conductor impedance, ohms per mile.
$\quad = \sqrt{r^2 + x^2}.$

$C =$ capacity in microfarads per mile.

$g =$ leakage conductance to neutral, in microhms per mile.
$\quad = \omega CK.$

$b =$ capacity susceptance to neutral, microhms per mile.
$\quad = \omega C.$

y = dielectric admittance per mile in microhms
$= \sqrt{g^2 + b^2}.$

$$\left.\begin{aligned} \text{If } K &= 0 \\ \text{and } r &= 0 \end{aligned}\right\} \text{then} \left\{\begin{aligned} g &= 0 \\ z &= x \end{aligned}\right. \qquad \text{and } y = b,$$

and the expression for the velocity of propagation reduces to

$$v = \frac{10^{-3}}{\sqrt{LC}}.$$

As the e.m.f. extends outward, it is being alternated at its source, but each successive instantaneous value travels independently of what follows it. Hence, the voltage at any given point

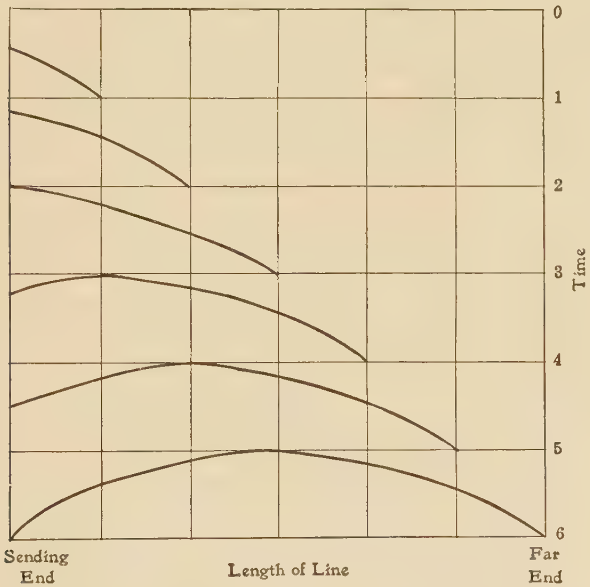

FIG. 33.—Progress of a wave on a transmission line.

on the line alternates in synchronism with that at the sending end. The voltage on the line may thus be represented by a series of diagrams representing successive brief intervals of time, like a movie film (Fig. 33).

It will be noted that, while a half cycle of voltage time wave has been passed through at the sending end, a half wave of voltage space curve has developed in the cable.

The length of the wave is given by the formula

$$\lambda = \frac{2\pi}{\beta} = \frac{v}{f}.$$

Thus at 60 cycles, the wave length (assuming zero attenuation) would be about 3,100 mi., at 10,000 cycles about 18 mi., and at 1,000,000 cycles about 0.186 mi.

In practical cases, therefore, cable transmission lines are very much shorter than the wave length of the applied fundamental voltage, but may be of the same order as the wave length corresponding to some high harmonic of the fundamental voltage.

If, in the course of its progress, the voltage wave comes to a transition point in the circuit, on one side of which the surge impedance is $\sqrt{\frac{L_1}{C_1}}$ and on the other side of which it is $\sqrt{\frac{L_2}{C_2}}$, the voltage wave is split into two, a reflected wave, which runs back toward its origin, and a refracted wave, which goes into the new section. The refracted voltage wave will be greater or less than the original wave, depending upon whether the new section is of less or

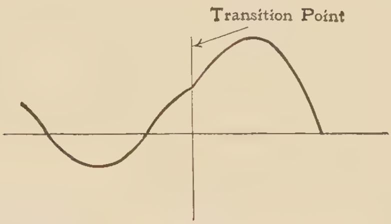

FIG. 34.—Transition point in transmission line shown by break in voltage-space curve.

greater surge impedance. The ratio of the voltages will equal the square root of the ratio of the surge impedances. As the instan taneous value of the voltage must be the same in the two sections, at the transition point, and as the maximum values of the voltage are different in the two sections, the phase angles of the waves must change at the transition point, as shown in Fig. 34. The reflected wave is equal to the difference between the original wave and the refracted wave.

In the case shown in Fig. 34, the reflected wave will be negative, so that, as it progresses back to the origin, it will cut down the original voltage wave. If, on the other hand, the voltage drops at the transition point, the reflected wave will add itself to the original wave as it speeds back to the origin.

Every transition point is thus a transformation point at which either the voltage rises and the current falls, or *vice versa.*

The most marked kind of transition point is, of course, an open end and the reflection therefrom is naturally the most important case.

If a reflected wave gets back to the starting point at the moment when a second impulse, of opposite direction, is sent into

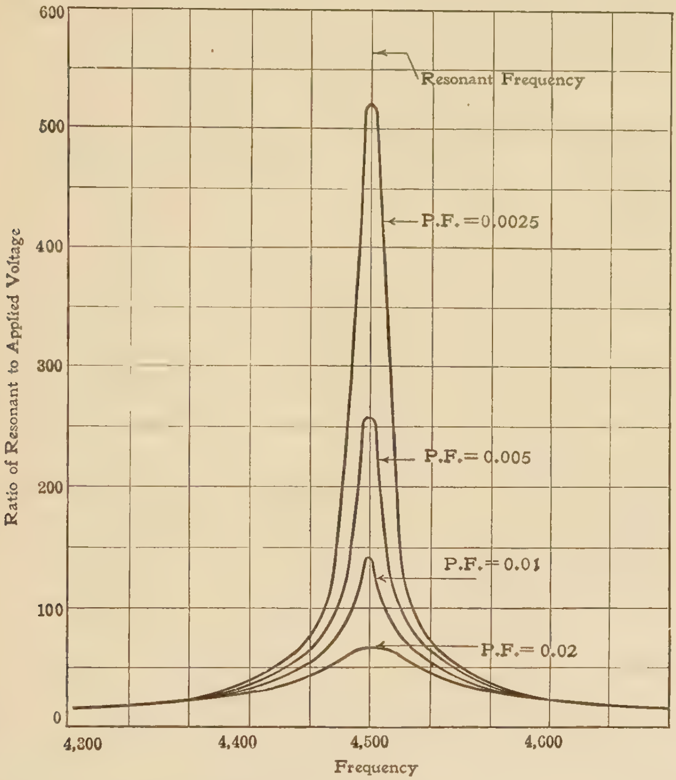

FIG. 35.—Resonance in a three phase circuit 10 mi. long, composed of three single-conductor cables 600,000 cir. miles with $^{40}/_{64}$ paper. Copper losses neglected, but power factor of insulation considered.

the line, the reflection of the first impulse adds itself to the second impulse; the return of this increased second impulse by reflection adds to the third impulse, and so on; that is, if alternating impulses succeed each other at intervals equal to the time required by an impulse to travel over the line and back, the effects of

successive impulses add themsleves, and large currents and high e.m.fs. may be produced by small impulses. The cumulative effect of such reflected waves is shown in Fig. 35, conductor losses, but not dielectric losses, being neglected.

There is, of course, a current wave as well as a voltage wave, or, to put the matter more correctly, there is a current component as well as a voltage component of the energy wave. This also is reflected and produces excessive currents when the voltage component is low.

On very long lines there will be points called nodes where an ammeter inserted in the circuit theoretically shows a root-mean-square value of zero, if the current-space wave is sinusoidal. It is, however, not possible to obtain a sinusoidal distribution of current and this theoretical condition is, therefore, almost impossible of realization.

ATTENUATION

The attenuation of waves in transmission lines has, until recently, been rather neglected by writers on the subject, as they have generally had in mind aerial lines in which it is not very serious, at 60 cycles, except where there is corona. Cables differ from these in having greater capacity, less inductance and more leak-ance, using the last term in its most general sense.

The attenuation constant α is such that the amplitude of each wave diminishes by the factor α as the wave travels unit distance.

The attenuation constant may be derived from the formula

$$\alpha = 10^{-3}\sqrt{\tfrac{1}{2}(yz - bx + gr)}.$$

Consider the effect of different power factors upon the performance of the line. If the attenuating effect of line resistance, including skin effect, be taken into account, instead of the resonance effects shown in Fig. 35, the milder ones shown in Fig. 36 will be obtained. A further reduction will be shown if sheath losses are taken into account. These curves are based on a line 10 mi. long composed of three single-conductor 500,000-cir. mil cables with $^{40}\!/\!_{64}$ in. of insulation.

It was found that the resonant frequency of this line is 960 cycles and the speed of propagation 42,000 mi. per second. It is interesting to note how rapidly the resonance condition falls off as the frequency rises or falls.

RESONANCE

The condition of resonance of a transmission line, known as quarter-wave resonance, has been described and it is obvious

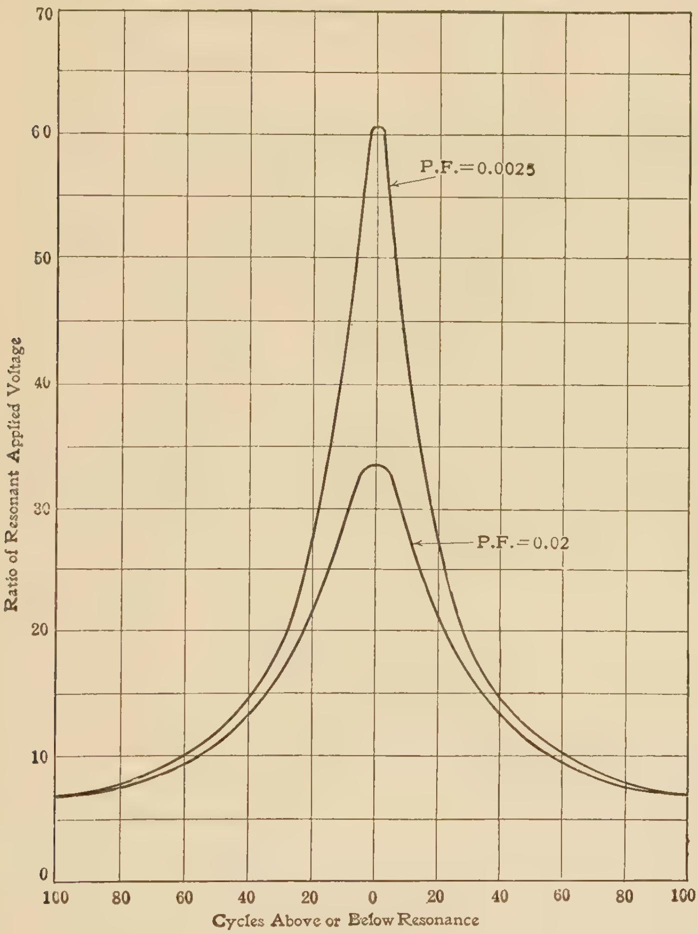

Fig. 36.—Resonance in circuit similar to that in Fig. 35, except that conductor resistance, including skin effect, is taken into account.

that such resonance will occur when the length of the line l is equal to $\frac{\lambda}{4}$.

The wave length in miles, however, is equal to

$$\frac{2\pi}{\beta}.$$

Hence the resonant frequency of a line is given by

$$l = \frac{\pi}{2\beta}.$$

or

$$\beta = \frac{\pi}{2l}.$$

The resonant frequency may be derived from β, but the complicated formula for β, given above can be solved only by trial and error.

At low frequencies, a section or group of sections of cable, or the entire cable, or the cable and transformers may resonate to some particular frequency. Thus, if a voltage wave having several harmonics is impressed on the circuit, resonance may occur between any or all of these and some particular part or parts of the circuit.

At high frequencies, however, the inductance is not constant but depends upon the frequency, so that the resonant frequency is less definite. Indeed, a high frequency is almost certain to find some element or group of elements of the circuit to resonate with. Ordinarily, these high-frequency surges are quickly damped out by the line losses, and they cannot become continuous or cumulative unless excited by a continuous supply of energy.

Two other conditions may arise from the redistribution of energy in a circuit, which are likely to prove injurious to cables, namely, continuous high-frequency surges due to arcing or sparking grounds and brief impulses of steep wave front.

In order to illustrate the former of these conditions, consider a single-conductor cable supported in the air, suspended, say, by insulating cords. If a difference of potentials is established between the conductors and ground, part of the potential will be carried by the cable insulation proper, and part by the surrounding air.

The air and the cable insulation may be considered as the dielectrics of two condensers in series, and the voltage relations derived from the principles governing these well-known devices. Consider two condensers in series, across which a potential difference of V volts is impressed.

Let C_1 and C_2 be capacitances of these condensers and V_1 and V_2 the potential drops across them respectively. Then

$V_1 + V_2 = V$ and, as the condensers necessarily carry the same charge Q,

$$V_1C_1 = V_2C_2 = Q.$$

Hence

$$V_2 = \frac{V}{1 + \dfrac{C_2}{C_1}}.$$

Consider the case of a conductor of radius r, insulated to a radius R with a material of specific capacity k, covered with a conducting sheath to a radius R_s. Consider the sheath to be separated from ground by an air space of such width that the outer limit of the air space is at radius R_a and assume that this air space covers $\frac{1}{m}$th the circumference of the sheath. These radii may be expressed in any unit, provided they are all in the same unit. The conductor and its insulation may be considered as two condensers in series, one of them having a capacity C_1, consisting of the insulation proper between conductor and sheath, and the other having capacity C_2, consisting of the air between the sheath and ground. Using the well-known formulas for the capacitance of concentric cylinders, the following relation is obtained:

$$\frac{C_2}{C_1} = \frac{\log_{10}\dfrac{R}{r}}{mk\log_{10}\dfrac{R_a}{R_s}}.$$

Combining the above equations,

$$V_2 = \frac{V}{1 + \dfrac{\log_{10}\dfrac{R}{r}}{mk\log_{10}\dfrac{R_a}{R_s}}}.$$

Now assume a 26,000-volt impregnated-paper lead sheathed single-conductor cable. This is enclosed in, but insulated from, another sheath, with an air film between them covering 10 deg. of arc. The dimensions, in centimeters, will be assumed to be as shown in Fig. 37.

The voltage across the air gap is plotted in Fig. 38 for various widths of air gap. It is interesting to note that gaps over 2 mm. wide carry almost the entire voltage, relieving the cable insulation of all but 2 or 3 kv.

Such a condition, however, is impossible of realization, as these air gaps will break down at a lower voltage.

Referring to Fig. 39, a half sine wave of the voltage between conductor and ground is shown. The line *a-a* represents the voltage at which the air space sparks over. The wave of poten-

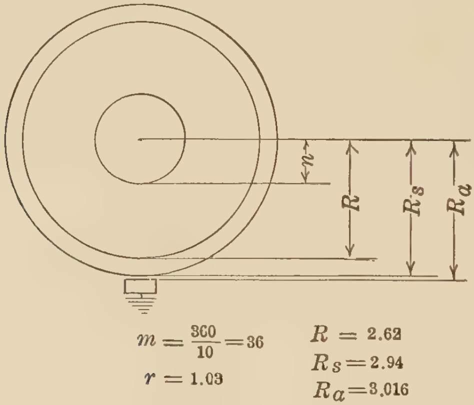

FIG. 37.—Cable sheath insulated from ground.

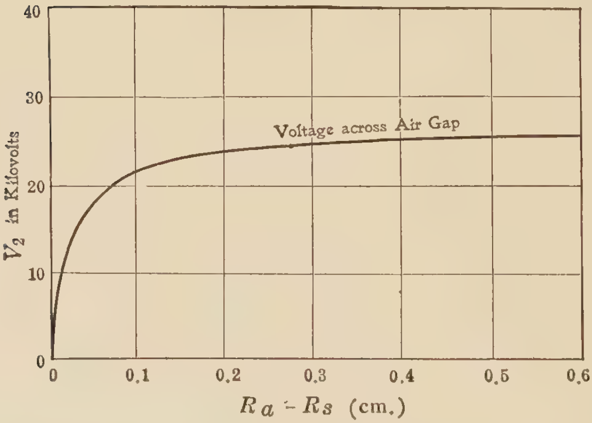

FIG. 38.—Voltage between sheath and ground for cable shown in Fig. 37.

tial across the air space will have the form of the saw-tooth curve because the voltage across the gap will rise until it attains the breakdown value indicated by *a-a* and will then drop to practically zero. This will stop the flow of sparks and the voltage will rise until it again attains the value *a-a* and the cycle will be repeated. The voltage across the cable insulation will be the difference between the sine wave and the air-gap wave, *i.e.*,

it will have the form shown by the saw-tooth curve in Fig. 40. Actual oscillograms show more the appearance of the curve in Fig. 41.

The frequency of the saw-tooth harmonic in this way may be anywhere from a few thousand to several hundred thousand cycles per second.

It may be shown theoretically, and has been verified experimentally, that high-frequency surges caused by sparking or arcing ground extend only a few hundred feet along a cable.

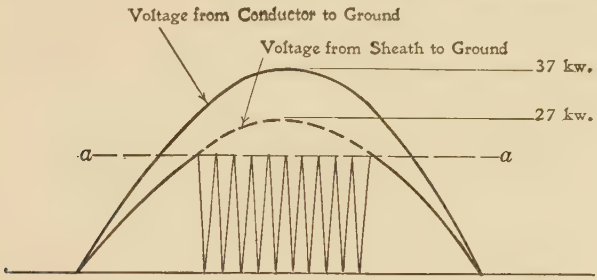

Fig. 39.—Transient due to periodic break-down of air-gap between cable sheath and ground.

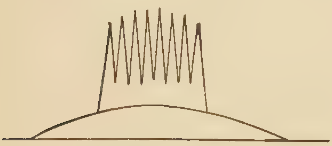

Fig. 40.—Transient voltage across cable insulation, due to break-down of air-gap between sheath and ground.

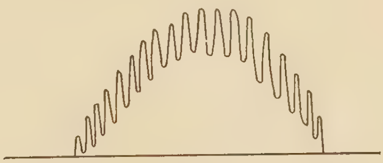

Fig. 41.—Oscillogram of transient voltage across insulation due to arcing ground.

In a specific case where the frequency was about 50,000 cycles, the voltage decreased 25 per cent in 380 ft.

Due to the change of inductance with frequency, the so-called constants of the cable are not exactly constant. The frequencies of the very high harmonics are, therefore, not definite, but are to some extent variable, since when they are close to each other they overlap. For this reason, Steinmetz says that:

> At very high frequencies, a transmission line has no definite frequency of oscillation, but can oscillate with any frequency. A long-distance transmission line has a definite natural period of oscillation, a relatively low fundamental frequency and its overtones, but can also oscillate with any frequency whatever, provided that this frequency is very high.

The very high frequencies set up by "static" disturbances are, therefore, very liable to give rise to dangerous potential rises and should be avoided by proper grounding of the sheaths. These ground connections, to be effective, should be close enough together to be effective in view of the skin-effect resistance of the sheaths at such frequencies.

In the case of single-conductor cables used on three-phase circuits with grounded neutral, "static" can be avoided by connecting together the sheaths of the three cables, because the instantaneous sum of the three-sheath potentials is zero. In the case of triplex cables on grounded neutral systems the sheath potential will be generally kept at zero by virtue of the mutually neutralizing action of the potentials induced by the three conductors but it is safer to ground the sheath.

If, however, a three-phase system is without grounded neutral, serious disturbances are likely to occur, even with the sheaths connected together, as the potential of the whole system may be raised very high above ground.

If the spark or arc is of variable length, the frequency of the saw-tooth wave will change correspondingly, and it may easily cover such a range of frequencies as to include the resonant ones of the system. In this way the disturbance may suddenly change from being a minor local one to being of a serious and widespread character.

Cases have been noted where the electromagnetically induced high voltage on the secondary of a transformer has induced charges on the primary, electrostatically, sufficient to establish a sparking ground on the primary, which created high-frequency oscillations in both primary and secondary.

A very interesting point was brought out by N. H. Slaughter and W. F. Wolfe[1] in connection with tests on power transformers for high-voltage transmission lines. They showed that a 60-cycle transformer will operate as a transformer for frequencies up to about 10,000 cycles, whereas at frequencies above 50,000 cycles it will act as a condenser. Between 10,000 and 50,000 cycles it acts as a combination of transformer and condenser and gives rise to resonance effects.

There remain to be considered only those dangerous conditions arising from a wave, or train of waves, of steep front.

[1] *Jour. A.I.E.E.*, Apr., 1924.

Thus far all waves have been considered as sinusoidal. If of more rectangular form, or even if sinusoidal but of very high frequency, the voltage which successively reaches each point of the line is not gradually applied, but appears at once at practically its full value. This sudden application of a high voltage starts a puncture of the insulation which may be completed by a succession of such impulses. Solid insulation is punctured by sudden impulses at much lower voltages than are required under normal conditions.

Surges of this character may originate from an accidental arc or spark, a lightning disturbance or a short circuit on some part of the system, and may raise the potential of a system at points many miles away from the origin of the disturbance.

The surges may pass through transformers, buses, reactors. etc., changing from voltage transients to current transients or *vice versa*, at transition points. It is not unusual to find dangerous voltage rises occurring 10 to 20 mi. away from a disturbing current surge.

The failure of cable insulation under the influence of transients is probably due in the first place to excessive electrostatic charges which break to ground outside the insulation proper, thereby starting an impulse. This impulse breaks up into local high-frequency traveling waves. These waves puncture the insulation and produce surges which may become manifest at great distances, and cause other failures.

The whole subject of abnormal potential rises in cable systems is of great importance, as it is estimated that at least half of all cable failures in service are due to them. As these transient voltages naturally pick out the weaker spots in cables, there is a natural tendency to blame the cables and belittle the transients.

As the amount of low-dielectric-loss cables in use increases, this proportion will undoubtedly grow, due both to the reduction of the number of failures due to cumulative heating, and to the decreased attenuation of transient waves.

Most of the research work which has been done on this subject has been in connection with aerial open-wire circuits or telephone lines, and, therefore, a big field is open for those who care to pursue the subject further, in connection with underground transmission lines.

A fascinating mathematical treatment of the subject has been given by Oliver Heavside in his "Electromagnetic Theory."

Due, however, to his treatment of mathematical operators as if they were actual quantities, his deductions have not been accepted by all physicists as rigorous proofs.

The latest and most complete exposition of the subject is that given by J. R. Carson in "Theory of the Transient Oscillations of Electrical Network and Transmission Systems."[1]

A series of references to important papers on the subject of transients in cables, is given on p. 198.

[1] *Trans. A.I.E.E.*, vol. 38, p. 345, 19.

CHAPTER XIII

DESIGN OF CABLES FOR CURRENT AND VOLTAGE

FEATURES OF DESIGN

Two phases of design must be carefully distinguished, namely, the formulation of complete specifications for the finished product and the preparation of manufacturing instructions to enable these specifications to be complied with. This chapter will be confined to the former phase, *i.e.*, to the one which interests the purchaser and user of cable.

This phase of design may again be divided into three parts:

1. Design to carry current.
2. Design to stand voltage.
3. Design to withstand handling.

Design to carry current is a matter of ascertaining the copper cross-section required to carry the given current, assuming that the dielectric loss and the heat-dissipating characteristics of the installed cable are known.

The formulas and tables given in Chap. X may be used for this purpose.

It is not always economical to operate cables at their full carrying capacity, as the energy loss in the copper may cost more than the annual charges on additional cables. Kelvin's law states that the minimum annual cost is obtained when the fixed charges on the investment equal the cost of the energy loss.

Sometimes Kelvin's law has to be forgotten, because there is no room in the street for more cables, or for some other equally good practical reason.

Sometimes the current to be carried by a cable is limited by the voltage regulation desired. For instance, if a cable is to be operated with a temperature rise of 45° C., the resistance rise will be 18 per cent. This may seriously interfere with the regulation.

It is possible to generalize about the "instantaneous" breakdown voltage of cables as a function of the dimensions of the

insulation because of the results of innumerable factory tests made under definite known conditions.

It is not so easy to generalize about the breakdown voltage for long periods of stress, as the experience for such generalizations must come from practical operation, where the conditions are indefinite and imperfectly known. Thus, the moment a cable becomes a part of a feeder system, it is subject to unknown and unknowable surge voltages.

While, therefore, it is now easy for a competent manufacturer to design a cable which will stand an ordinary factory test, experience is lacking when it comes to designing a cable to meet service conditions where unprecedentedly high voltages are concerned.

Indeed, the whole matter of high-voltage cables is at present in a state of uncertainty. Few of the very high-voltage cables, *i.e.*, cables for operation at over 30,000 volts, are giving perfect satisfaction.

Therefore, when discussing the principles involved, it should be remembered that manufacturers and users are working at the limit of their proved knowledge.

One of the great difficulties in predetermining cable performance is that cables change their properties when they are bent. Every bending of a cable involves a stretching of the lead on the outside of the bend and, as lead is inelastic, it buckles when the cable is straightened, thereby forming voids between the paper and the lead. If these voids happen to be on the under side of the cable, the oil drips into them from other parts of the cable; if they happen to be on the upper side, they remain as voids and ionize under stress.

If the oil is too stiff, bending the cable tears the films of oil and the parts separate, leaving narrow vacuous passages, which also ionize.

The danger of ionization is not so much due to the extra dielectric loss as to the local high-voltage surges which are likely to be set up by corona or sparking in the air film. In other words, the "static" effect described in the last chapter can occur inside the cable as well as outside.

The designing of cables to carry voltage is further complicated by the fact that the cable must be able to withstand the "instantaneous" breakdown test, the 5- or 15-min. high-voltage factory test, the test after installation, the service voltage and

such surges as may ordinarily be expected to occur in normal operation.

TRIPLEX CABLES

In the case of triplex-sector impregnated-paper cables, the thickness of insulation required to withstand a given instantaneous breakdown voltage may be calculated from the formula

$$t = \frac{E}{g},$$

where E is the given voltage and g is the dielectric strength of the insulation. As a matter of fact, the breakdown stress is

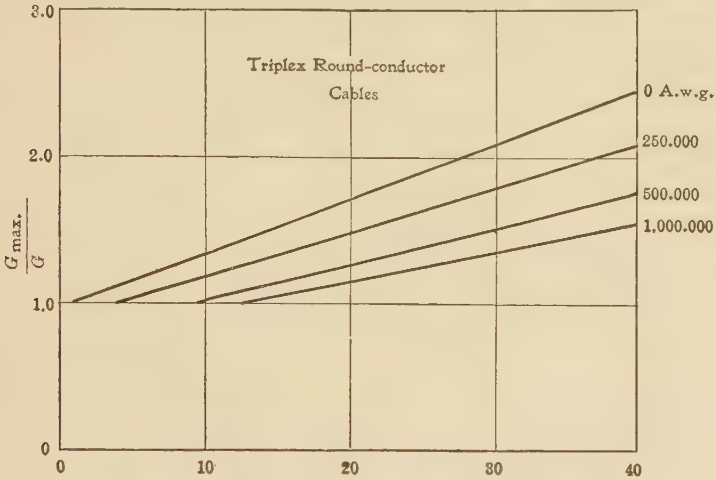

FIG. 42.—Ratio of maximum to average stress in triplex round-conductor cables.

rather less for thick than for thin insulation, but this may be due to the less thorough impregnation. This varies from 125 to 150 kv. per centimeter for high-class cables. If g be taken as 125 kv. per centimeter for a cable required to attain 200 kv. between conductors, before failure

$$t = \frac{200}{125} = 1.6 \text{ cm.} = \frac{40}{64} \text{ in.}$$

Hence each conductor will have to be covered with $^{20}/_{64}$ of insulation.

The 5-min. full-reel test voltage is usually about 50 to 40 per cent of the instantaneous short-length test, and experience

shows that, if the insulation is proportioned to meet the latter, it will pass the former satisfactorily.

The working stress remains to be considered. It is conceivable that a cable may pass the instantaneous and 5-min. tests and yet may fail in service because of air ionization. Ionization occurs when the stress in the insulation adjacent to the air film exceeds about 20 kv. per centimeter, but it does not become dangerous unless the stress is 25 to 30 kv. per centimeter and not always at those values. Higher stresses seem to be allowable with small conductors.

The average stress in sector cables will not exceed the above limits, if the breakdown stress is taken as five times the working voltage, but the maximum stress may be considerably greater, the amount depending on the form of sector as shown by R. W. Atkinson, Jour. A.I.E.E., 1924. (See Appendix IX.)

In the case of round-conductor cables, the ratio of maximum to average stress is greater, as shown in Fig. 42. It will be noted that on the circular mil sizes (*i.e.*, 250,000 cir. mils and larger), if the insulation does not exceed $^{10}\!/_{64}$ in. on each conductor, the ratio of maximum to average stress is practically unity, but that, for smaller sizes and thicker insulations, it may exceed even 2. Thus, on a 350,000-cir. mil $\frac{19 \times 7}{64}$ round-conductor cable, operating at 33 kv., the average stress between conductors will be 21.9 kv. per centimeter but the maximum will be about 29, which is above the safe value in view of ionization. If, however, $^{22}\!/_{64}$ of insulation are used, the average and maximum stress will be 19 and 25 kv. per centimeter respectively, which latter is fairly safe from the point of view of ionization.

In a triplex cable for use on a three-phase system with grounded neutral, the voltage from each conductor to sheath is $\frac{1}{\sqrt{3}} =$ 0.58 of that between conductors. Hence, each conductor should be insulated between conductors for 50 per cent of the line voltage and to sheath for 58 per cent. Obviously, the simplest way would be to insulate each conductor for 50 per cent of the line voltage and to place a belt over all conductors, good for 8 per cent of the line voltage.

If it could be assumed that the breakdown voltage of insulation were proportional to its thickness, the belt would have to be

only 8 per cent of the thickness of insulation between conductors, *i.e.*, 16 per cent of the individual-conductor insulation thickness.

It was noted in Chap. XI, however, that such proportionality holds only where the escape of heat is normal to the electric field, whereas the breakdown voltage is proportional to the square root of the thickness where the escape of heat is parallel to the electric field.

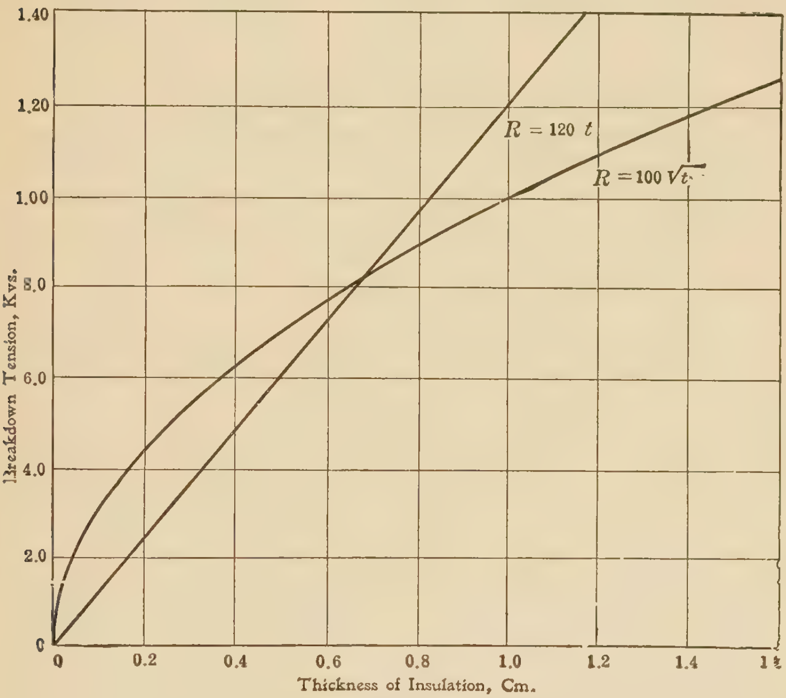

FIG. 43.—Relation between break-down voltage and insulation thickness, triplex cables.

Since the escape of heat from the insulation between conductors is toward the sheath, it is approximately normal to the electric field, so that between sector conductors the law of proportionality holds, provided the conductors are not so small as to introduce an energy distance factor. On the other hand, the escape of heat from the insulation between conductors and sheath, while also toward the sheath, is here parallel with the electric field, so that the square-root law holds here.

The straight-line and square-root relations are plotted in Fig. 43 and it is obvious that for thin insulation the dielectric is

stronger when the heat escapes parallel to the electric field. With thick insulation, the dielectric is stronger when the heat escapes at right angles to the electric field.

It is not known exactly what thickness corresponds to the crossing point, but the average dielectric strength of thick belts is considerably lower than that of the insulation between conductors, the ratio being about 80 per cent in the case of the usual designs of high tension cables. It would be interesting and useful to find where the two curves actually cross.

SINGLE-CONDUCTOR CABLES

If the insulation around a cylindrical conductor of radius r is a concentric cylinder of radius R, and it has the same electrical characteristics in all directions, it is easy to show that the electric stress at a point distant x cm. from the axis, when a voltage E kv. is applied across the insulation, is

$$g = \frac{E}{x \log_\epsilon \frac{R}{r}} \cdot \text{ in kilovolts per centimeter.}$$

The form of the curve between g and x, R and E being fixed, is as shown in Fig. 44.

It is also clear that $g_{\text{max.}}$ corresponds to $x = r$ and $g_{\text{min.}}$ to $x = R$.

If R is made fixed, and r variable, $g_{\text{max.}}$ may be plotted against r and a curve like the one shown in Fig. 45 obtained. The reason for this shape is that, as r is increased, two opposing influences are at work: first, a reduction of field intensity due to the greater surface of conductor on which the radial lines of force impinge, and, second, an increase of field intensity due to the reduced thickness of insulation. For small values of r, the former tendency predominates, for large values the latter.

A minimum value is attained for $\frac{R}{r} = 2.72$.

Now unfortunately neither impregnated-paper nor varnished-cambric insulation has equal electrical properties in all directions. In the case of impregnated paper, the comparison would be about as follows:

Property	Ratio $\frac{\text{Parallel to Paper}}{\text{Perpendicular to Paper}}$
Dielectric strength	1/10
Specific capacity	3/4
Resistivity (electric)	Less than unity
Heat resistivity	Less than unity

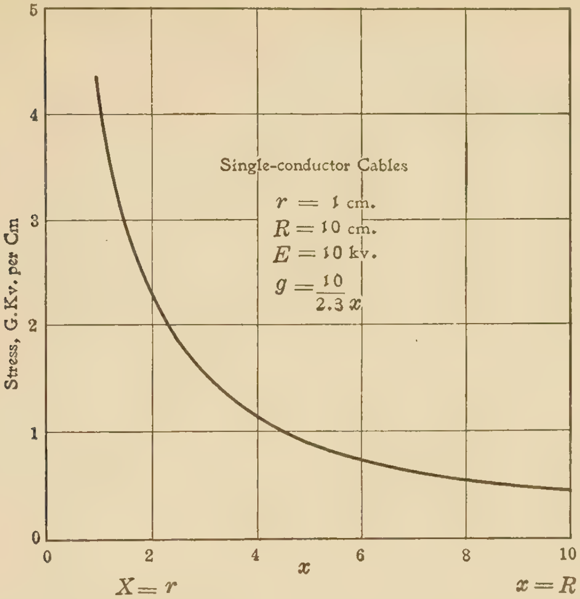

FIG. 44.—Relation between stress and distance from conductor.

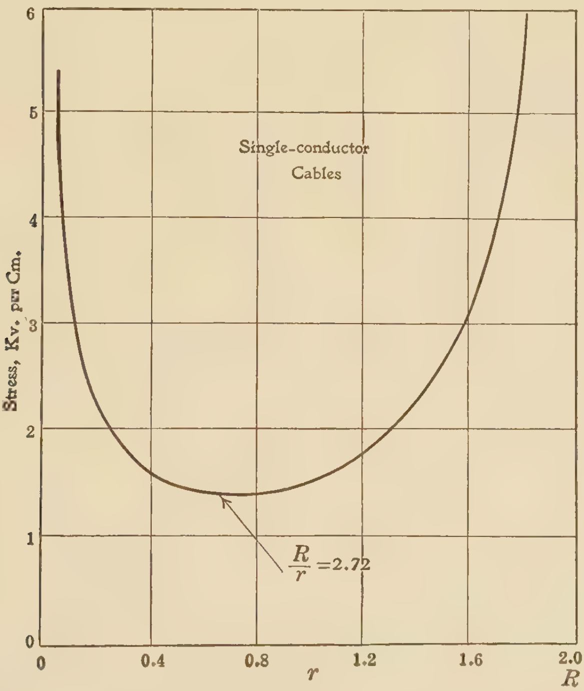

FIG. 45.—Relation between stress and radius of conductor.

The situation is further complicated by the fact that this formula neglects the energy distance factor, which was explained in a previous chapter.

For this reason other formulas have been suggested by Fernie, Wiseman and Peek. The last of these is based upon the ionic theory and takes into account energy distance. In other words, it is the formula originally developed for corona in air, later applied to transformer oil and finally to impregnated paper.

This formula has been found to apply to thick insulation, but not to thin walls on large conductors. It is as follows:

$$E = G(r + 1.2\sqrt{r}) \log_\epsilon \frac{R}{r}$$

where G = dielectric strength, kilovolts per centimeter, *i.e.*, the potential gradient at the energy distance, at failure.
r = radius of conductor.
R = outside radius of insulation.
E = breakdown voltage, kilovolt.

With this formula, if R and E be kept constant, the relation between G and r will be as shown by curve A in Fig. 46. Curve B is the corresponding relation for $G_{\text{max.}}$, *i.e.*, the stress of the conductor surface, which is given by

$$G_{\text{max.}} = G\left(1 + \frac{1.2}{\sqrt{r}}\right)$$

or derived directly from the formula

$$G_{\text{max.}} = \frac{E}{r \log_\epsilon \frac{R}{r}}.$$

Thus, with single-conductor cables as with triplex, the thickness of insulation to stand a given instantaneous-test voltage may be calculated by a formula involving dielectric strength

The ratio of $\frac{G_{\text{max.}}}{G}$ is given by the formula

$$\frac{G_{\text{max.}}}{G} = 1 + \frac{1.2}{\sqrt{r}},$$

which for values of r from 0.5 to 1.5 gives a ratio departing but little from 2 (Fig. 47). In single-conductor cables of 00 A. w. g. to 1,000,000 cir. mils, the maximum stress is about twice the stress at the energy distance.

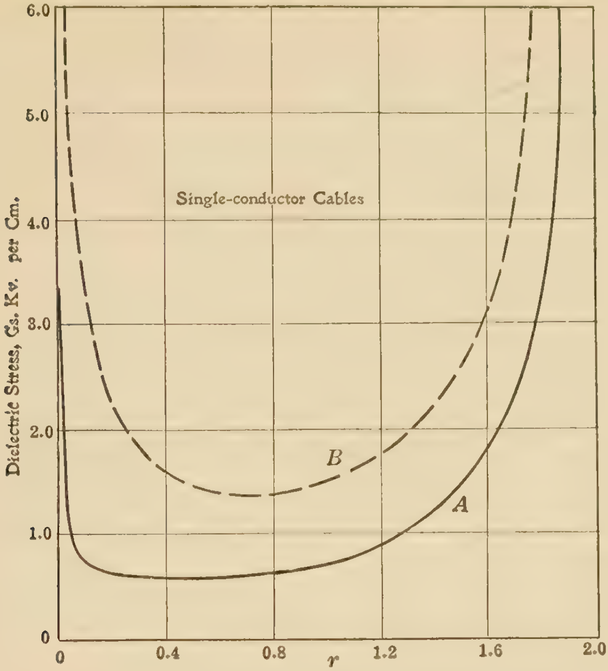

FIG. 46.—Relation between dielectric stress and conductor diameter in a cable of fixed external diameter. *A*, according to Peek's formula. *B*, according to ordinary logarithmic formula.

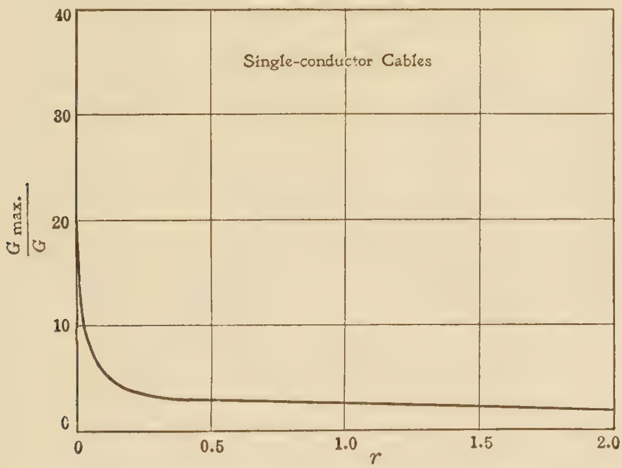

FIG. 47.—Ratio of maximum stress to stress at energy distance, in single-conductor cables.

It has been found that the G used in this formula is the same as the g used in the formula for triplex cables. Hence if a cable is designed for $G = 25$ kv. per centimeter working pressure, $G_{max.}$ will be about 50 kv. per centimeter which will give rise to dangerous air ionization. Therefore, G for the working voltage cannot be of the order of one-fifth of G for breakdown, as is often the case with triplex cables, but must be about one-tenth.

Thus, a 500,000-cir. mil cable with $^{40}/_{64}$ of insulation operating at 26 kv. will have a stress of 13 kv. per centimeter at the energy distance and a maximum stress of 26 kv. per cm. Well-made cables of this type, however, have stood a maximum stress of 40 kv. per centimeter for a week without developing hot spots.

A 500,000-cir. mil cable with 1 in. of insulation, operating at 38 kv. to ground, would have a stress of 14.3 kv. per centimeter at the energy distance and 28.5 kv. per centimeter maximum.

Some European cables are operating satisfactorily at maximum stresses of over 30 kv. per centimeter, but they have conductors of small diameter.[1]

The dangerous stress from the point of view of ionization must, therefore, depend upon the position and size of the occluded vapor pockets and upon the size of conductor.

RUBBER-INSULATED CABLES

Rubber-insulated cables are usually made without belt insulation, as the conductor insulation must be vulcanized before cabling the conductors together. If a belt should then be applied and vulcanized, the conductor insulation would receive a second vulcanization with consequent reduction of quality. Low-voltage cables, however, are made in this way, as the mechanical construction may make it worth while to sacrifice a certain amount of quality in the insulation.

Single-conductor rubber-insulated cables are usually designed by the ordinary logarithmic formula $E = Gr \log_\epsilon \frac{R}{r}$, except that for values of $\frac{R}{r}$ greater than 2.72 it has been found that

$$E = \frac{RG}{2.72},$$

[1] Our present theories do not satisfactorily differentiate between high stresses due to thin insulation and those due to small conductors; there appears to be more difference than can be explained by energy distance.

i.e., the breakdown voltage is independent of the radius of the conductor and depends only on the outside radius of the insulation. The specific capacity of rubber insulation is about 5. Hence, thin air films in the insulation will ionize at a stress of about 17 kv. per centimeter in the rubber.

Hence, if $\frac{R}{r} > 2.72$, ionization occurs when

$$E = 6.25R.$$

Thus a cable of 3-cm. radius with a conductor of 1-cm. radius would carry continuously only about 19 kv.

Because of its high specific capacity rubber insulation is peculiarly effective in throwing high stresses upon adjacent air

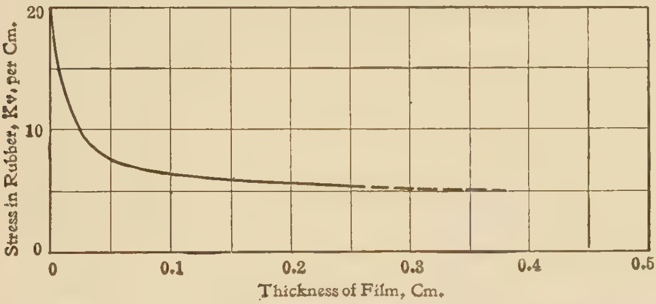

FIG. 48.—Stress in rubber at which ionization will occur in contiguous air films of various thicknesses.

films, be they within the insulation or without. The stresses at which ionization occurs is shown in Fig. 48.

Thus, a rubber-insulated No. 4 A. w. g. wire with $\frac{6}{64}$ in. of insulation, operating at 2,300 volts above ground, will have a stress at its outer surface of

$$G = \frac{2.3}{0.497 \log_\epsilon \frac{0.497}{0.259}} = 8.3 \text{ kv. per centimeter.}$$

Hence the air in immediate contact with it will be stressed to 45 kv. per centimeter, which is dangerous from the ionization standpoint.

If, on the other hand, the insulation thickness were $\frac{8}{64}$ in., the stress would be

$$G = \frac{2.3}{0.577 \log_\epsilon \frac{0.577}{0.259}} = 5 \text{ kv. per centimeter.}$$

The stress in the contiguous air would be 25 kv. per centimeter which is perfectly safe for thin films.

This principle, reflected in actual operation, led to a change, a few years ago, from $6/64$ to $8/64$ as the standard insulation for 2,300-volt wires.

Varnished-cambric cables are designed by rule of thumb. No scientific data on their performance are yet available. This type of cable is used at high voltage only for station wiring and much of it is carried on porcelain insulators.

CHAPTER XIV

INSULATION RESISTANCE, HYSTERESIS LOSS AND EDDY-CURRENT LOSS

INSULATION RESISTANCE

While the function of insulation is primarily to interpose resistance between conductors at different potentials, the resistivity of the insulating materials used for cables is so high that it does not demand serious attention.

The whole story is told, from a practical point of view, by the following rule prepared by a committee of the A.I.E.E. for inclusion in the Standards of that Institute. The only importance of the matter is that certain antiquated municipal regulations specify minimum insulation resistance for cables or networks, and it is therefore necessary to have standard expressions for purposes of comparisons.

Calculation of Insulation Resistance. *Single-conductor Cables.* The insulation resistance shall be calculated by the following equation:

$$R = K \log_{10} \frac{D}{d}.$$

Where $R =$ the insulation resistance in megohms for a specified unit length.

$K =$ megohms constant. When it corresponds to a mile unit of length, k megohm-miles $= 0.00000228 \times$ resistivity of the insulation in megohm-centimeters.

$D =$ outside diameter of insulation.

$d =$ diameter of conductor.

Multiple-conductor Cables, Concentric.—The insulation resistance between the inner conductor and the adjacent conductor of a concentric cable shall be calculated as in the case of a single-conductor cable. The insulation resistance between any other conductor and its adjacent conductors, or conductor and sheath (if the sheath is adjacent) of a concentric cable, is the product divided by the sum of the resistance of the layers of insulation

adjacent to such conductor, each being calculated separately as in the case of a single-conductor cable.

Multiple-conductor Cables, Non-concentric, Round or Sector Type.—The insulation resistance of each conductor to all other conductors connected to the sheath or water shall be calculated assuming the multiple-conductor cable to be replaced by a single-conductor cable having a round conductor of the same cross-sectional area and an outside diameter over insulation of $D = d +$ twice the equivalent thickness of the insulation.

No mathematical formula has been developed for this "equivalent thickness," so that no exact expression for the insulation resistance can be given for multiple-conductor cables. For all practical purposes, however, since a variation of 10 or 15 per cent in insulation resistance is unimportant, the following equations may be used:

For two-, three- and four-conductor cables:

$$R = K \log_{10} \frac{(d + 3c + 2b)}{d},$$

where d is the diameter of a round conductor of the same cross-sectional area.

c is the thickness of conductor insulation.

b is the thickness of belt insulation.

Where the braid or outer surface of the insulation acts as a conducting surface (as is sometimes the case in multiple-conductor, rubber-insulated cables), the values of D shall be as in single-conductor cables.

The constant K depends upon the nature, dryness and temperature of the insulation.

The most commonly used values are as follows:

Insulation	K at 15.5° C. (60° F.)
Impregnated paper	500
Varnished cambric	400
Rubber (30 per cent hevea)	4,000

In the case of impregnated paper, the effect of temperature is very erratic, but it is known that the resistivity falls off rapidly with rising temperature, the slope of the curve being greatest in the neighborhood of the melting point of the compound and least when the compound is liquid.

The resistivity of varnished-cambric insulation falls very rapidly above 75° C.

The temperature coefficients vary with the type of compound used, both in impregnated-paper, rubber and varnished-cambric insulation, and therefore differ with the manufacturer and the date of manufacture.

HYSTERESIS LOSS

If a single conductor cable carrying alternating current be enclosed in an iron conduit or armor, the iron will be subjected to rapidly alternating magnetism.

Whenever iron is magnetized successively in opposite directions, a loss of energy occurs in the iron, which is called hysteresis loss. The effect of this hysteresis loss is to allow more current to flow through the circuit when a given voltage is applied.

If both wires of a circuit, or all three wires in the case of a three-phase circuit, be enclosed in the same conduit or armor, the hysteresis loss will be small, as the outgoing and return currents largely neutralize one another, as far as magnetizing the conduit or armor is concerned.

EDDY-CURRENT LOSS

If a single conductor carrying alternating current be paralleled by a metallic body—such as another wire, an enclosing sheath of lead, a metallic conduit pipe or armor—the rings of magnetism, as they close in on the conductor, not only induce a current in it, but also in the parallel metallic body. Such eddy currents produce energy losses, due to the ohmic resistance of the metallic body in which current is induced.

The effect of eddy-current loss in such foreign bodies is similar to that of hysteresis loss. In other words, it causes more current to flow through the original circuit when a given voltage is applied. The case of three single-conductor metal-sheathed cables carrying alternating currents is so important that a special chapter will be devoted to it.

CHAPTER XV

INDUCTANCE AND IMPEDANCE

The inductance of a circuit depends upon the area embraced by that circuit. Hence, if the outgoing and return wires are kept close together, as in a small two- or three-conductor cable, there being but little area enclosed between them, the inductive drop will be very slight. In the case of large conductors, the inductive effect may be quite appreciable.

Table XIV gives values for the inductance, reactance and impedance of round three-conductor cables. All values are on the basis of single phase and for one conductor of the cable, 1 mi. long. The so-called three-phase values would be 1.73 times the table values.

The table values are calculated from the following equation:

Let L = inductance in millihenrys per mile of each conductor.
r = actual radius of the conductor.
D = distance between conductor centers expressed in same units as r.

$$L = 0.08047 + 0.741 \log_{10} \frac{D}{r}.$$

If the conductors are several inches or feet apart, the inductive drop is liable to exceed the ohmic drop. If there is any iron between the wires, more magnetism will be induced than if only air and other non-magnetic materials were present, and the inductive drop will be correspondingly greater. That is one reason why the outgoing and return wires in the case of a-c. house-distribution systems are always put in the same conduit pipe.

In recent years a-c. transmission lines have come into vogue in which the current in each of the three phases is carried by a separate cable. Submarine crossings in such lines are effected by means of steel-wire armored cables. In these lines, the voltage is so high that the inductive drop, which depends only on the current, is not necessarily a high percentage of the impressed voltage (see Chap. XIX).

TABLE XIV.—INDUCTANCE, REACTANCE AND IMPEDANCE, AT 60 CYCLES, OF THREE-CONDUCTOR CABLES

Area, circular mils B.&S. No.	Diameter, inches	Resistance per mile, ohms[1]	Insulation thickness in sixty-fourths of an inch[2]											
			3/64 by 3/64			4/64 by 4/64			5/64 by 5/64			6/64 by 6/64		
			Ind. M. H.	Reac. ohms	Imp. ohms	Ind. M. H.	Reac. ohms	Imp. ohms	Ind. M. H.	Reac. ohms	Imp. ohms	Ind. M. H.	Reac. ohms	Imp. ohms
500,000	0.814	0.116	0.338	0.127	0.172	0.349	0.131	0.175	0.360	0.136	0.178	0.370	0.140	0.182
450,000	0.772	0.129	0.340	0.128	0.181	0.351	0.132	0.184	0.362	0.137	0.189	0.373	0.141	0.191
400,000	0.728	0.145	0.343	0.129	0.195	0.354	0.134	0.197	0.367	0.138	0.201	0.377	0.142	0.204
350,000	0.681	0.166	0.346	0.130	0.211	0.357	0.135	0.214	0.370	0.140	0.217	0.380	0.143	0.220
300,000	0.630	0.194	0.349	0.132	0.235	0.361	0.136	0.237	0.374	0.141	0.240	0.386	0.145	0.244
250,000	0.575	0.233	0.353	0.133	0.268	0.366	0.138	0.271	0.381	0.144	0.274	0.394	0.149	0.277
0000	0.528	0.275	0.357	0.135	0.308	0.372	0.140	0.309	0.387	0.146	0.313	0.403	0.152	0.316
000	0.470	0.346	0.362	0.136	0.373	0.379	0.143	0.375	0.397	0.150	0.378	0.411	0.155	0.381
00	0.418	0.437	0.369	0.139	0.460	0.388	0.146	0.461	0.406	0.153	0.464	0.423	0.160	0.466
0	0.373	0.550	0.377	0.142	0.569	0.398	0.150	0.571	0.417	0.157	0.572	0.432	0.163	0.573
1	0.332	0.695	0.384	0.145	0.711	0.405	0.152	0.713	0.429	0.162	0.715	0.447	0.168	0.716
2	0.292	0.879	0.393	0.148	0.893	0.417	0.157	0.894	0.441	0.166	0.896	0.463	0.174	0.896
3	0.260	1.11	0.403	0.152	1.12	0.431	0.162	1.12	0.454	0.171	1.12	0.476	0.180	1.12
4	0.232	1.40	0.413	0.156	1.41	0.442	0.167	1.41	0.469	0.177	1.41	0.494	0.186	1.41
6	0.184	2.21	0.437	0.165	2.22	0.470	0.177	2.22	0.501	0.189	2.22	0.529	0.200	2.22

(*William Nesbit, Electric Journal*, 1919.)

[1] Based upon 100 per cent conductivity at 25° C. (77° F.), including 2 per cent allowance for spiral of strands and 2 per cent allowance for spiral of conductors. For a temperature of 65° C. (149° F.) these resistance values would be increased 15 per cent.

[2] The inductance (ind.) is in millihenrys; the reactance (reac.) and the impedance (imp.) are in ohms. The table values were derived from the equation $L = 0.08047 + 0.741 \log_{10}\frac{D}{R}$ per mile, where R is the radius of conductor, D the distance between centers of conductors expressed in same terms as R, and L the inductance in millihenrys per mile of each conductor.

All values in table are single-phase and based upon a single conductor 1 mile long.

TABLE XIV.—(*Continued*)

Area, circular mils B.&S. No.	Diameter, inches	Resistance per mile, ohms[1]	Insulation thickness in sixty-fourths of an inch[2]											
			7/64 by 7/64			8/64 by 8/64			9/64 by 9/64			10/64 by 10/64		
			Ind. M. H.	Reac. ohms	Imp. ohms	Ind. M. H.	Reac. ohms	Imp. ohms	Ind. M. H.	Reac. ohms	Imp. ohms	Ind. M. H.	Reac. ohms	Imp. ohms
500,000	0.814	0.116	0.379	0.143	0.184	0.389	0.146	0.186	0.398	0.150	0.190	0.407	0.153	0.192
450,000	0.772	0.129	0.384	0.145	0.194	0.393	0.148	0.195	0.403	0.152	0.200	0.411	0.155	0.202
400,000	0.728	0.145	0.389	0.147	0.206	0.396	0.149	0.208	0.409	0.154	0.212	0.417	0.157	0.230
350,000	0.681	0.166	0.395	0.149	0.222	0.402	0.151	0.224	0.415	0.157	0.229	0.423	0.160	0.231
300,000	0.630	0.194	0.399	0.150	0.245	0.409	0.154	0.246	0.421	0.158	0.251	0.431	0.162	0.254
250,000	0.575	0.233	0.409	0.154	0.279	0.419	0.158	0.282	0.430	0.162	0.285	0.442	0.166	0.286
0000	0.528	0.275	0.415	0.157	0.318	0.427	0.161	0.320	0.441	0.166	0.323	0.452	0.170	0.323
000	0.470	0.346	0.429	0.162	0.383	0.440	0.166	0.385	0.455	0.172	0.388	0.466	0.176	0.389
00	0.418	0.437	0.439	0.166	0.467	0.455	0.171	0.471	0.469	0.177	0.473	0.483	0.182	0.474
0	0.373	0.550	0.453	0.171	0.578	0.466	0.176	0.578	0.485	0.183	0.580	0.498	0.188	0.582
1	0.332	0.695	0.466	0.176	0.718	0.483	0.182	0.697	0.501	0.189	0.720	0.516	0.195	0.721
2	0.292	0.879	0.483	0.182	0.900	0.502	0.189	0.900	0.521	0.196	0.902	0.537	0.202	0.902
3	0.260	1.11	0.499	0.188	1.13	0.519	0.195	1.13	0.538	0.203	1.13	0.558	0.211	1.13
4	0.232	1.40	0.518	0.195	1.41	0.538	0.203	1.41	0.558	0.210	1.42	0.577	0.218	1.42
6	0.184	2.21	0.557	0.210	2.22	0.580	0.219	2.22	0.601	0.226	2.22	0.622	0.234	2.22

(*William Nesbit*, *Electric Journal*, 1919.)

[1] Based upon 100 per cent conductivity at 25° C. (77° F.), including 2 per cent allowance for spiral of strands and 2 per cent allowance for spiral of conductors. For a temperature of 65° C. (149° F.) these resistance values would be increased 15 per cent.

[2] The inductance (ind.) is in millihenrys; the reactance (reac.) and the impedance (imp.) are in ohms. The table values were derived from the equation $L = 0.08047 + 0.741 \log_{10} \frac{D}{R}$ per mile, where R is the radius of conductor, D the distance between centers of conductors expressed in same terms as R, and L the inductance in millihenrys per mile of each conductor.

All values in table are single-phase and based upon a single conductor 1 mile long.

TABLE XIV.—(*Continued*)

Area, circular mils B.&S. No.	Diameter, inches	Resistance per mile, ohms[1]	Insulation thickness in sixty-fourths of an inch[2]											
			11/64 by 11/64			12/64 by 12/64			13/64 by 13/64			14/64 by 14/64		
			Ind. M. H.	Reac. ohms	Imp. ohms	Ind. M. H.	Reac. ohms	Imp. ohms	Ind. M. H.	Reac. ohms	Imp. ohms	Ind. M. H.	Reac. ohms	Imp. ohms
500,000	0.814	0.116	0.417	0.157	0.195	0.427	0.161	0.198	0.434	0.164	0.202	0.441	0.166	0.202
450,000	0.772	0.129	0.423	0.160	0.204	0.431	0.162	0.208	0.439	0.165	0.211	0.449	0.170	0.211
400,000	0.728	0.145	0.429	0.161	0.216	0.436	0.164	0.220	0.446	0.168	0.222	0.457	0.172	0.224
350,000	0.681	0.166	0.436	0.164	0.235	0.446	0.168	0.237	0.453	0.171	0.240	0.464	0.175	0.240
300,000	0.630	0.194	0.444	0.167	0.256	0.456	0.172	0.260	0.461	0.174	0.262	0.473	0.178	0.264
250,000	0.575	0.233	0.454	0.171	0.289	0.465	0.175	0.292	0.475	0.179	0.295	0.486	0.183	0.296
0000	0.528	0.275	0.465	0.175	0.328	0.476	0.180	0.330	0.486	0.183	0.332	0.498	0.188	0.334
000	0.470	0.346	0.481	0.181	0.392	0.493	0.186	0.395	0.503	0.190	0.396	0.516	0.194	0.398
00	0.418	0.437	0.498	0.188	0.476	0.510	0.192	0.479	0.521	0.196	0.480	0.535	0.202	0.482
0	0.373	0.550	0.514	0.194	0.584	0.528	0.199	0.586	0.539	0.203	0.589	0.554	0.209	0.590
1	0.332	0.695	0.531	0.200	0.724	0.546	0.206	0.725	0.559	0.211	0.726	0.573	0.216	0.728
2	0.292	0.879	0.554	0.209	0.905	0.570	0.215	0.906	0.583	0.220	0.908	0.598	0.225	0.910
3	0.260	1.11	0.574	0.216	1.13	0.591	0.222	1.13	0.606	0.228	1.13	0.618	0.233	1.14
4	0.232	1.40	0.596	0.224	1.42	0.613	0.231	1.42	0.627	0.236	1.42	0.643	0.242	1.42
6	0.184	2.21	0.643	0.242	2.22	0.661	0.249	2.22	0.678	0.256	2.22	0.696	0.262	2.23

(*William Nesbit, Electric Journal*, 1919.)

[1] Based upon 100 per cent conductivity at 25° C. (77° F.), including 2 per cent allowance for spiral of strands and 2 per cent allowance for spiral of conductors. For a temperature of 65° C. (149° F.) these resistance values would be increased 15 per cent.

[2] The inductance (ind.) is in millihenrys; the reactance (reac.) and the impedance (imp.) are in ohms. The table values were derived from the equation $L = 0.08047 + 0.741 \log_{10} \frac{D}{R}$ per mile, where R is the radius of conductor, D the distance between centers of conductors expressed in same terms as R, and L the inductance in millihenrys per mile of each conductor.

All values in table are single-phase and based upon a single conductor 1 mile long.

TABLE XIV.—(*Continued*)

Area, circular mils B.&S. No.	Diameter, inches	Resistance per mile, ohms[1]	Insulation thickness in sixty-fourths of an inch[2]											
			16/64 by 16/64			18/64 by 18/64			20/64 by 20/64			22/64 by 22/64		
			Ind. M. H.	Reac. ohms	Imp. ohms	Ind. M. H.	Reac. ohms	Imp. ohms	Ind. M. H.	Reac. ohms	Imp. ohms	Ind. M. H.	Reac. ohms	Imp. ohms
500,000	0.814	0.116	0.457	0.172	0.208	0.474	0.179	0.212	0.487	0.183	0.217	0.501	0.189	0.222
450,000	0.772	0.129	0.462	0.174	0.218	0.481	0.181	0.224	0.496	0.187	0.228	0.509	0.192	0.232
400,000	0.728	0.145	0.471	0.178	0.230	0.487	0.183	0.235	0.505	0.190	0.240	0.519	0.196	0.244
350,000	0.681	0.166	0.480	0.181	0.246	0.496	0.187	0.252	0.513	0.193	0.254	0.529	0.200	0.260
300,000	0.630	0.194	0.491	0.185	0.270	0.511	0.192	0.274	0.526	0.198	0.279	0.541	0.204	0.282
250,000	0.575	0.233	0.505	0.190	0.302	0.524	0.197	0.306	0.541	0.204	0.311	0.557	0.210	0.314
0000	0.528	0.275	0.517	0.195	0.338	0.536	0.202	0.342	0.556	0.210	0.348	0.573	0.216	0.352
000	0.470	0.346	0.536	0.202	0.403	0.556	0.209	0.406	0.575	0.217	0.410	0.592	0.223	0.415
00	0.418	0.437	0.552	0.208	0.486	0.578	0.218	0.490	0.599	0.226	0.494	0.618	0.233	0.496
0	0.373	0.550	0.575	0.217	0.592	0.601	0.226	0.596	0.621	0.234	0.599	0.641	0.242	0.602
1	0.332	0.695	0.598	0.225	0.732	0.623	0.235	0.734	0.645	0.243	0.737	0.666	0.251	0.740
2	0.292	0.879	0.623	0.235	0.912	0.649	0.245	0.914	0.674	0.254	0.917	0.693	0.261	0.920
3	0.260	1.11	0.649	0.245	1.14	0.674	0.254	1.14	0.698	0.262	1.14	0.721	0.272	1.14
4	0.232	1.40	0.673	0.254	1.42	0.701	0.264	1.43	0.725	0.273	1.43	0.746	0.281	1.43
6	0.184	2.21	0.725	0.273	2.22	0.754	0.284	2.23	0.780	0.294	2.23	0.809	0.305	2.23

(*William Nesbit*, *Electric Journal*, 1919.)

[1] Based upon 100 per cent conductivity at 25° C. (77° F.), including 2 per cent allowance for spiral of strands and 2 per cent allowance for spiral of conductors. For a temperature of 65° C. (149° F.) these resistance values would be increased 15 per cent.

[2] The inductance (ind.) is in millihenrys; the reactance (reac.) and the impedance (imp.) are in ohms. The table values were derived from the equation $L = 0.08047 + 0.741 \log_{10} \frac{D}{R}$ per mile, where R is the radius of conductor, D the distance between centers of conductors expressed in same terms as R, and L the inductance in millihenrys per mile of each conductor.

All values in table are single-phase and based upon a single conductor 1 mile long.

In the case of single-conductor band-armored cables, the inductance and the combined hysteresis and eddy-current loss with 60-cycle current are so great with large currents that it is impracticable for such cables, in long feeders, to carry more than 8 to 10 amperes. Such cables are, therefore, used almost entirely for series-lighting systems, which seldom require over 8 amperes.

The characteristics of common sizes of single-conductor park cables are given in Tables XV to XIX, inclusive.

Table XV.—Resistance, Reactance and Impedance of Single-conductor Park Cables at 60 Cycles, 30° C., Carrying 6.6 Amperes

Ohms per 1,000 Ft.

Distance apart of outgoing and return cables	No. 6 A. w. g.			No. 8 A. w. g.		
	Resistance	Reactance	Impedance	Resistance	Reactance	Impedance
In same trench, touching	0.419	0.249	0.488	0.653	0.249	0.700
4 ft. apart	0.419	0.616	0.745	0.653	0.616	0.890
Opposite sides of street	0.419	0.742	0.853	0.653	0.742	0.990

Table XVI.—Resistance, Reactance and Impedance of Single-conductor Park Cables at 60 Cycles, 30° C., Carrying 7.5 Amperes

Ohms per 1,000 Ft.

Distance apart of outgoing and return cables	No. 6 A. w. g.			No. 8 A. w. g.		
	Resistance	Reactance	Impedance	Resistance	Reactance	Impedance
In same trench, touching	0.419	0.348	0.569	0.653	0.384	0.758
4 ft. apart	0.419	0.638	0.764	0.653	0.638	0.857
Opposite sides of street	0.419	0.775	0.882	0.653	0.775	1.026

Table XVII.—Resistance, Reactance and Impedance of Two-conductor Park Cables at 60 Cycles, 30° C.

Ohms per 1,000 Ft.

Size A.w.g.	Resistance	Reactance	Impedance
No. 6	0.838	0.093	0.842
No. 8	1.300	0.100	1.374

Table XVIII.—Watts Loss per 1,000 Ft. of Single-conductor Park Cable at 30° C., 6.6 Amperes, 60 Cycles

Distance apart of outgoing and return cables	No. 6 A. w. g. Eddy current and			No. 8 A. w. g. Eddy current and		
	I^2R	Hysteresis	Total	I^2R	Hysteresis	Total
In same trench, touching..	18	3	21	28	3	31
4 ft. apart..............	18	10	28	28	10	38
Opposite sides of street...	18	16	34	28	16	44

Table XIX.—Watts Loss per 1,000 Ft. of Single-conductor Park Cable at 30° C., 7.5 Amperes, 60 Cycles

Distance apart of outgoing and return cables	No. 6 A. w. g. Eddy current and			No. 8 A. w. g. Eddy current and		
	I^2R	Hysteresis	Total	I^2R	Hysteresis	Total
In same trench, touching..	24	4	28	37	4	41
4 ft. apart..............	24	14	38	37	14	51
Opposite sides of street...	24	20	44	37	20	57

CHAPTER XVI

FORCES BETWEEN CONDUCTORS

The current in a cable causes an attraction or repulsion between conductors, depending upon whether the currents are flowing in the same or in opposite directions. Where the currents are in quadrature, there is no attraction or repulsion.

Two Parallel Single-conductor Cables.

Let F = force between cables, pounds per foot.

I_1 = current in one cable.

I_2 = current in other.

a = axial distance between cables, inches.

Then,

$$F = \frac{5.39\, I_1 I_2 \times 10^{-7}}{a}.$$

Three-phase Cable.

Let F = average force repelling conductor from center of cable.

F_m = maximum force repelling conductor from center of cable (with sine wave).

I = r.m.s. current per phase (all phases equal).

a = axial distance between conductors, inches.

$$F = \frac{4.67\, I^2 \times 10^{-7}}{a}.$$

$$F_m = \frac{9.34\, I^2 \times 10^{-7}}{a}.$$

Two Conductors of Three-phase Cable.—Assuming one phase of a triplex cable to be dead, and equal currents in the other two, the repulsion will be as follows:

Let F = average force repelling conductors from one another.

F_m = maximum force repelling conductors from one another (with sine wave).

I = r.m.s. current per phase.

a = axial distance between conductors, inches.

$$F = \frac{5.39\, I^2 \times 10^{-7}}{a}.$$

$$F_m = \frac{10.78\, I^2 \times 10^{-7}}{a}.$$

The maximum forces are important because the inertia of the masses concerned is not very great.

The above formulas are derived from the well-known principle that the force between conductors is proportional to the product of the currents in the conductors and varies inversely as the distance between them.

In the case of a No. 000 triplex cable with 7/16 in. of insulation between conductors, the average repulsive force would be as follows:

Amperes per Conductor	Force, Pounds per Foot of Cable
1,000	0.52
10,000	52.0
20,000	208.0
40,000	832.0
70,000	2550.0
100,000	5200.0

CHAPTER XVII

AERIAL CABLES

Power companies are steadily coming more and more to make use of high-voltage three-conductor cables suspended from messenger wires attached to poles. The reason is purely one of economy, because it is less expensive to use poles, which in most cases are already in place, than to construct underground conduits where only one or possibly two circuits are required along a given street or highway.

Of course, open wires on insulators and cross-arms are less expensive than cables, but there are many cases where open-wire circuits for operation at transmission voltages are impracticable, as in built-up streets, where they are unsafe, or where there are trees which introduce maintenance difficulties.

The telephone companies have used cables in this way for many years and have standardized the accessories and procedures for installation, especially for lead-sheathed cables.

Three types of cables are used, however, paper-lead, paper-and-reinforced-rubber, and varnished-cambric.

Paper-insulated, lead-covered aerial cables are similar to underground cables of the same type in all respects, except that aerial cables have either 3 per cent of tin or 1 per cent of antimony mixed with the lead of the sheath, to prevent the crystallization which is liable to take place in pure-lead sheaths, due to the vibration caused by winds. The telephone companies have thousands of miles of aerial cables with lead sheaths containing either 3 per cent of tin or about 1 per cent of antimony, and do not experience trouble from crystallization.

The use of the paper-insulated, lead-covered type of aerial cable is recommended wherever practicable, as it is preferable fromalmost every standpoint.

Both the paper-and-reinforced-rubber and the varnished-cambric types are provided with steel-armor tape and an outside tape or braid, usually of saturated jute. This makes the outside diameter greater than that of the paper-lead type, with

consequent greater sleet and wind load, which often exceeds the saving in weight due to the omission of lead.

A lead sheath is highly desirable, as it is moistureproof, and therefore makes possible the use of impregnated-paper insulation, with its well-known advantages for high-tension transmission voltages, without the danger of chemical action between oil and rubber. This type can also be taken down at a later date, if desirable, and installed in underground conduit.

A further advantage of the lead sheath is its immunity from weather conditions. In the other types the covering over the armor has to be repainted every three to five years. Even with care, the jute covering will peel off, presenting an unsightly appearance and exposing the armor to oxidation.

Aerial cables are supported on galvanized-steel messenger cables by clips or rings, spaced about a foot apart.

The usual method of installation is to set the rings on the messenger cable and pull the cable through them by a winch and pulling rope. Special appliances are provided for raising the cable from the reel to the level of the messenger cable.

CHAPTER XVIII

SUBMARINE CABLES

Submarine power cables may be divided into two classes:

1. Those which can readily be made up in one length and laid without splicing.

2. Those which are of such length or size that submerged splices are necessary.

For short crossings, such as those under small rivers, creeks and canals, the cables can readily be made in continuous lengths. Such cables generally have three conductors and are insulated

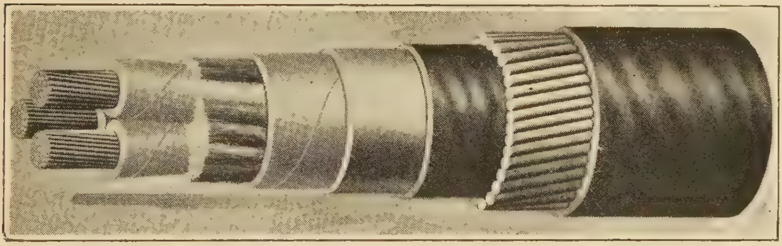

Fig. 49.—Typical paper-lead submarine cable.

with paper, protected against moisture by a lead sheath, and armored with helically wound galvanized-steel wire. Rubber or varnished-cambric insulation, or a combination of the two, may be used instead of the impregnated paper. When provided with a lead sheath, a portion of the insulation, unless it is rubber, is placed around all three conductors in order to obtain the minimum diameter.

Cables of the type described above are made up as follows:

Paper-lead (Fig. 49)

Insulation over conductor	Impregnated paper.
Fillers	Impregnated paper.
Belt insulation	Impregnated paper.
Covering over belt	Lead sheath.
Covering over lead	Jute saturated with asphaltum compound to prevent injury to lead sheath.

Armor	Galvanized steel wire run through asphaltum to prevent moisture entering between the armor wires and between them and the lead sheath.
Outside covering	Jute saturated with asphaltum compound and then passed through talc to prevent sticking.

Rubber-lead

Insulation over conductor	30 or 40 per cent hevea rubber.
Covering over insulation	Rubber-filled tape.
Fillers	Paraffined or tarred jute.
Covering over group of conductors	Rubber-filled tape.
Belt insulation	None.
Covering over tape	Lead sheath.
Covering over lead	Jute saturated with asphaltum compound to prevent injury to lead sheath.
Armor	Galvanized-steel wire run through asphaltum to prevent moisture entering between the armor wires and between them and the lead sheath.
Outside covering	Jute saturated with asphaltum compound and then passed through talc to prevent sticking.

Varnished-cambric-lead

Insulation over conductors	Varnished cambric.
Fillers	Paraffined jute.
Belt insulation	Varnished cambric.
Covering over belt	Lead sheath.
Covering over lead	Jute saturated with asphaltum compound to prevent injury to lead sheath.
Armor	Galvanized-steel wire run through asphaltum to prevent moisture entering between the armor wires and between them and the lead sheath.
Outside covering	Jute saturated with asphaltum compound and then passed through talc to prevent sticking.

Rubber-varnished-cambric-lead

Same as last, except 30 or 40 per cent hevea rubber insulation on conductors.

The paper-lead type is the most used of the lead-covered types of submarines.

Some engineers prefer to omit the outside covering of jute, as they consider it a useless expense, because it usually rots away after long-continued submersion. On the other hand, it does not add greatly to the cost of the cable, and it has the advantage of preventing the galvanizing of the armor wires from being scraped off in the process of laying, thus exposing the unprotected steel to corrosion.

Double armor, *i.e.*, either two layers of wire armor or one of tape covered by one of wire, is found necessary where there are rocks on the river bottom.

Where the crossings are so long that a lead-covered cable cannot be made in a single length for the entire distance because of manufacturing or shipping limitations, it is necessary to make splices. The earlier installations were made with cast-iron splicing boxes, which were sunk with the cable.

Experience indicates that these boxes possess the following serious disadvantages:

1. Their great weight is liable to cause sharp bends, tending to crack the lead sheath during handling. Also the boxes are clumsy and difficult to manipulate.

2. The boxes are liable to crack, since cast iron is not capable of withstanding severe tensional and torsional stresses, which are very likely to occur when the cable is being laid or if it becomes fouled with ships' anchors, or if there is shifting of the river bottom.

One of the most successful methods of making splices consists of using a lead sleeve and cutting the cable back under the armor far enough so that the armor wires from each end may lap over the sleeve. A wrought-iron pipe, previously slipped over the cable, is centered over the splice and supported on flanges. The armor wires are brought over the pipe, overlapped the length of the pipe and then securely bound by transverse wrappings or "seizings" of galvanized-steel wire.

It is, however, much better not to have splices at all, as experience has shown that splices frequently are the seat of electrical breakdown, whereas continuous cables may be operated for many years without any trouble of this kind.

Although up to the present time no general practice has been established for making long crossings with continuous lengths

of cables, the great advantages to be secured in doing so have led several power companies having this problem to contend with to install such cables.

These cables, in which the lead sheath has necessarily been omitted because it places a limit on the length of continuous sections, have proved highly successful and have been a great improvement over the old spliced cables. Rubber compound, since it is moistureproof, is the only insulating material which can be used where there is no lead covering. Such cables are generally made up as follows for three-phase circuits:

Number of conductors....	Three, tinned and stranded.
Insulation...............	30 or 40 per cent hevea rubber compound.
Covering over insulation..	One layer rubber-filled tape.
Grouping of conductors..	Twisted.
Fillers..................	Paraffined jute.
Covering over fillers......	Rubber-filled tape.
Bedding for armor.......	Two layers of jute, outer layer asphalted.
Armor..................	Spirally wound, galvanized steel.
Outside covering.........	Asphalted jute passed through talc to prevent sticking.

It should be noted that there is no belt insulation, and that the full thickness of rubber-insulating compound is provided around each conductor. This may make a rather large diameter where the conductors are large, but the absence of a lead sheath partially offsets this and also secures a lighter and more flexible cable. A cable of this kind is more economical to make and to install than a lead-sheathed cable.

A cable of the type described above, 7,000 ft. in length with three No. 00 conductors, has been successfully operated at 26,000 volts by the Shawinigan Water & Power Company at Three Rivers, Quebec, Canada for 15 years. One power company, which had a great deal of trouble from the cables in the Delaware River, at Wilmington, becoming fouled with ships' anchors, seems to have solved its difficulties by employing this construction. Formerly, whenever the spliced rubber-covered cables became fouled, they were almost invariably put out of service. The non-leaded, continuous cable, however, has withstood the ordeal of being caught by an anchor and tangled up with the spliced cables without interruption of service, while the latter, as usual, failed. In grappling for the damaged cables, in order to raise them out of the water for repairs, the non-leaded cable, tangled up with the others, was actually

pulled up on a scow without interfering to the slightest extent with its operation.

There are two ways of laying submarine cables: In one method the cable is mounted on shore and hauled across the water by a rope, and in the other the cable is mounted on a boat and paid off as the boat proceeds across the river.

In the former way a light cord is laid across the water from a small boat and is used to draw a heavy rope. This rope has a hook at one end, which is engaged with an eye attached to the projecting ends of armor wire of the cable. The rope is then wound on a winch on the opposite side of the water from the cable, thus drawing the cable across. It is obvious that this method of installation is suitable only for short lengths, *i.e.*, those not exceeding 1,000 ft. The actual speed of pulling is about 15 min. per 1,000 ft.

This method is, however, susceptible of modification so as to be applicable to lengths up to a mile, provided the water is sufficiently deep. A steel cable is laid across the water by means of a large rope previously pulled in place by a small one, as described above. The cable is then drawn across by a rope, as described above, except that it hangs on a trolley running along the messenger, which relieves the cable of extra tension caused by pulling it along a rock bottom. When the cable has been pulled across, it and the supporting steel cable are allowed to drop to the bottom.

In the second method of installing cable, an end is anchored to one shore while the boat crosses to the other. Sometimes the cable is mounted on a brake-controlled drum, and sometimes it is laid flat on the deck. In the latter case it is coiled somewhat in the form of a figure 8. This arrangement is necessary, as the cable is to be laid directly in the water from the boat and, by coiling it in this way, it can be run off without twisting or kinking. A twist or kink in a cable of such bulk and stiffness would injure it.

When preparing a cable end for pulling, special precautions must be taken to avoid injury caused by the armor wire squeezing the core. The usual way is to unwind the armor wire for a distance of 3 or 4 ft. and to cut back and seal the cable end in the ordinary way with a lead cap. A short piece of cable, say 6 in. long, called a "dummy," is then set against the cap to take the squeezing effect of the armor wires when the cable is pulled. The armor wires are carried several inches beyond the dummy and made into a loop for attachment to the pulling rope.

CHAPTER XIX

SINGLE CONDUCTOR CABLES FOR TRIPLEX CIRCUITS

The diameter limitations imposed by conduits and by the facility of handling determine the maximum thickness of insulation which may be used in triplex cables. With conductors of ordinary sizes, this thickness is in the vicinity of $^{20}/_{64}$ in. which, in the present state of the art, is not safe for operating voltages in excess of 33,000.

In order to carry higher voltages, single-conductor cables are resorted to, one for each phase.

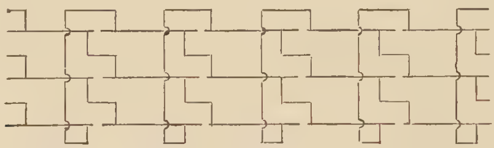

FIG. 50.—Transposition of sheaths of single-conductor cables for three-phase circuits.

For many years it was thought that the inductive effects in such circuits would prevent their practical use. Thus, in 1909 Steinmetz said:

> With single-conductor cables of higher voltages, in addition to the phenomena of losses, and possibly related to them, there appear a number of very high-frequency disruptive effects, some of them unexplained, which have. in a number of instances of station wiring, led to the abandonment of armored cables and even of lead-covered, single-conductor cables in favor of unarmored cables.

Ten years later Clark and Shanklin[1] said:

> Greater care must be taken to assure reliable and permanent bonding and grounding than with three-conductor cable. If one of the sheaths was accidentally freed of its bond connections, electromagnetic and electrostatic inductions would tend to raise it to a high potential. There would not only be danger of destroying the sheath or causing injury to workmen, but there would also be danger of exploding accumulated gases by electrostatic sparking.

Neglecting static effects for the present, and considering only electromagnetic induction, the voltages induced in the sheaths will establish such a difference of potentials between sheaths as to constitute a danger to men working in splicing chambers. Furthermore, any accidental short circuits between sheaths will result in local heating sufficient to endanger the sheaths by burning.

If, on the other hand, the sheaths be short-circuited, the dangerous voltages are eliminated, but sheath currents are introduced and these are likely to reduce considerably the carrying capacity of the cable, as described below.

A scheme has been suggested for combining the advantage of open- and short-circuited sheaths by inserting insulating joints at every manhole and transposing sheaths as shown in Fig. 50.

When considering the reduction of carrying capacity due to sheath currents, it must be remembered that three single-conductor cables have greater heat-dissipating ability than a triplex cable, so that, without the sheath losses, they have greater carrying capacity than the latter. The sheath loss is seldom great enough to overbalance this.

An advantage of the three-cable system is that all cable failures are grounds, which are much less serious than short circuits between phases.

If the cables cannot be disposed equilaterally, phase unbalancing will result. This can be remedied by transposition of conductors at splicing chambers. It is, however, not generally necessary to resort to this complication.

Sheaths should be grounded and cross-bounded at least every 1,000 ft. to reduce the effects of electrostatic induction.

THREE-PHASE CIRCUIT WITH LEAD-COVERED CABLES

Symbols.

b = radius of conductor, inches.
e = inner radius of lead sheath, inches.
f = outer radius of lead sheath, inches.
D = distance between centers of conductors, inches, assuming them to be set in an equilateral triangle.
M = mutual inductance of conductor and sheath, henrys per 1,000 ft.
E_s = e.m.f. induced per 1,000 ft. of sheath.

[1] *Trans. A.I.E.E.*, vol. 38–1, p. 950, 1919

$\omega = 2\pi f$, where f is the frequency.
I_c = r.m.s. current in conductor, amperes.
L_o = inductance of each cable with sheath open-circuited, henrys per 1,000 ft.
L_c = inductance of each cable with sheath short-circuited, henrys per 1,000 ft.
L_s = inductance of the sheath of each cable, henrys per 1,000 ft.
I_s = sheath current, amperes.
R_s = resistance of sheath, ohms per 1,000 ft.
W_s = power loss in sheath, watts per 1,000 ft.
W_c = power loss in conductor, watts per 1,000 ft.
R_c = resistance of conductor, ohms per 1,000 ft.
A = cross-sectional area of conductor in circular inches.

Formulas.—The basic formula required for these calculations is that which gives the mutual inductance between conductor and sheath. Several such formulas have been developed based upon various approximations, but the simplest and most useful is the following

$$M = 1.405 \times 10^{-4} \log_{10} \frac{2D}{e+f}.$$

This is based upon the assumption that the entire induction is concentrated at the mean radius of the sheath. It gives values about 1 per cent higher than the far more complicated formula developed by Alexander Russel, based upon an integration of the separate elements of induction in each infinitesimal layer of sheath.

The e.m.f. induced in the sheath is,

$$E_s = \omega M I_c.$$

The inductance L_o with sheaths open-circuited is derived from the well-known formula

$$L_o = \frac{0.152 + 1.4 \log_{10} \frac{D}{b}}{10^4}.$$

The inductance L_c with sheaths short-circuited is given by

$$L_c = L_o - M.$$

The sheath resistance is given by

$$R_s = \frac{0.036}{f^2 - e^2} \text{ ohms at } 40° \text{ C.}$$

When the sheaths are short-circuited through a bond of negligible resistance, the sheath current is given by

$$I_s = \frac{E_s}{\sqrt{R^2{}_s + (\omega L_s)^2}}$$

or

$$\frac{I_s}{I_c} = \sqrt{\frac{1}{\left(\frac{R_s}{\omega M}\right)^2 + \left(\frac{L_s}{M}\right)^2}}$$

$$L_s = \frac{1.4}{10^4} \log_{10} \frac{D}{f}, \text{ approximately.}$$

It is also approximately equal to M, in which case the formula becomes

$$\frac{I_s}{I_c} = \sqrt{\frac{1}{\left(\frac{R_s}{\omega M}\right)^2 + 1}}.$$

Let this ratio of currents be designated as p.

The ratio of the sheath losses to the conductor losses

$$\frac{W_s}{W_c} = \frac{I^2{}_s\, R_s}{I^2{}_c\, R_c}$$

$$= \frac{3p^2 A}{f^2 - e^2}.$$

The potential drops along the sheaths are 120 deg. apart in phase. Hence, if bonded together at any point, the difference of potentials between them at a point 1,000 ft. away will be 1.73 E_s.

Example.—Consider three cables, 4½ in. apart, each of 500,000-cir. mil area, with 40⁄64 of insulation and ⅛-in. lead. Assume 60 cycles and a current of 100 amperes in the conductor.

$b = 0.41.$ $e = 1.05.$ $f = 1.18.$ $D = 4.50.$

$$M = 1.405 \times 10^{-4} \log_{10} \frac{9.0}{2.23}.$$

$$= 0.853 \times 10^{-4} \text{ henrys per 1,000 ft.}$$

$$E_s = 377 \times 0.853 \times 100 \times 10^{-4}.$$

$$= 3.22 \text{ volts per 1,000 ft.}$$

$$L_o = \left(0.152 + 1.4 \log_{10} \frac{4.50}{0.41}\right) \times 10^{-4}.$$

$$= 1.61 \times 10^{-4}.$$

$$L_c = (1.61 - 0.853) \times 10^{-4}.$$

$$= 0.757 \times 10^{-4}.$$

$$R_s = \frac{0.036}{1.18^2 - 1.05^2} = 0.124 \text{ ohm.}$$

$$L_s = \frac{1.4}{10^4} \log_{10} \frac{4.50}{1.18} = 0.813 \times 10^{-4}$$

$$\frac{I_s}{I_c} = \sqrt{\frac{1}{\left(\frac{0.124 \times 10^4}{377 \times 0.853}\right)^2 + \left(\frac{0.813}{0.853}\right)^2}} = 0.252$$

or, by the other formula,

$$\frac{I_s}{I_c} = \sqrt{\frac{1}{\left(\frac{0.124 \times 10^4}{377 \times 0.853}\right)^2 + 1}}$$

$$= 0.251.$$

$$\frac{W_s}{W_c} = \frac{3 \times 0.252^2 \times 0.5}{1.18^2 - 1.05^2}$$

$$= 0.327.$$

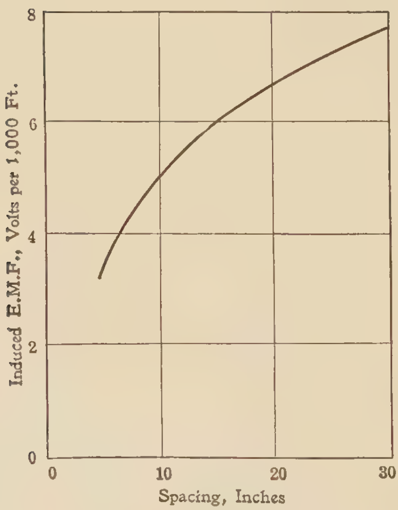

FIG. 51.—Relation between spacing of cables and voltage induced in sheaths.

It is of interest to consider this example in further detail, especially with reference to the effect of changing the spacing between cables.

Figure 51 shows the relation between spacing and induced voltage. It will be noted that the voltage varies from 3 to 8 volts per 1,000 ft. per 100 amperes in the conductor. Assuming

the lower figure for a line 10 mi. long with sheaths connected together at one end only, the difference of potential between sheaths at the other end will be:

$$1.73 \times 2 \times 5.28 \times 10 = 274 \text{ volts}$$

per 100 amperes in the conductor. With 300 amperes this would amount to 822 volts.

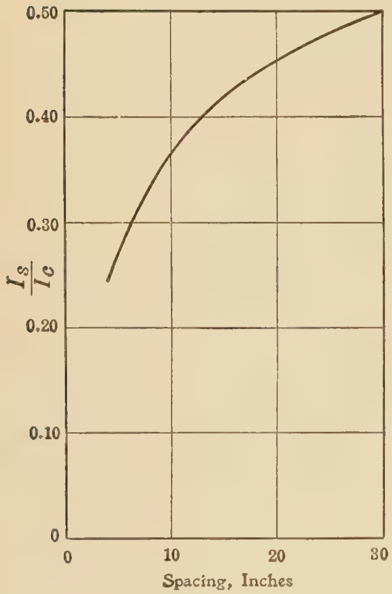

FIG. 52.—Sheath current in terms of conductor current for various cable spacings.

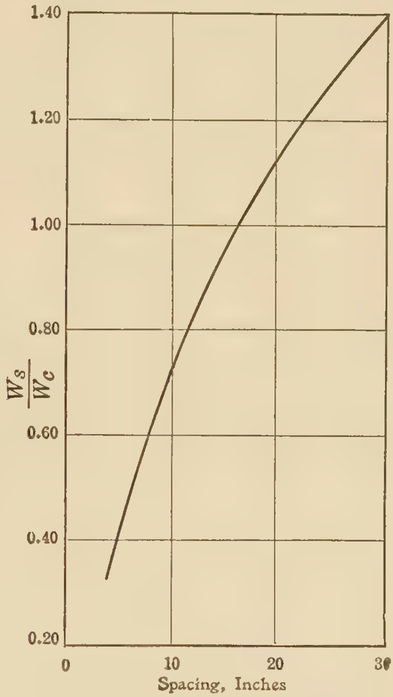

FIG. 53.—Sheath losses in terms of conductor losses for various cable spacings.

If the sheath be short-circuited by a bond of zero resistance, the induced (sheath) current will be related to the conductor current as shown by Fig. 52.

With short-circuited sheaths the loss in the sheaths will be related to the conductor loss, as shown in Fig. 53. It will be noted that, at spacings over 16 in., the sheath loss exceeds the conductor loss.

The subject of electrostatic induction, and consequent high-frequency local surges, was treated in Chap. XII.

Sheath Currents and Carrying Capacity.—The effect of sheath currents upon the carrying capacity of a cable may be calculated by a modification of the formula

$$I = \sqrt{\frac{1}{r}\left(\frac{\theta}{R} - W\right)},$$

which was given in Chap. X.

It is only necessary to substitute for the thermal resistance from conductor to ground ($R = R_1 + R_2$) the larger quantity $R' = R_1 + R_2 \left(1 + \frac{W_s}{W_c}\right)$, where R_1 is the thermal resistance from conductor to sheath, and R_2 that from sheath to ground.

For example, consider the three 500,000-cir. mil cables rated above. If

$$R_1 = 145$$
$$R_2 = 90$$

then

$$R' = 145 + 90(1 + 0.327)$$
$$= 264, \text{ as against } R = 235.$$

With negligible dielectric loss, the carrying capacity would be reduced 6 per cent by the sheath losses.

ARMORED CABLES

It was shown by J. B. Whitehead[1] that the ratio of the total flux in the armor of an armored single-conductor cable to the flux that would exist if the armor wire were replaced by air is

$$k = \frac{1}{a}\left\{\frac{\pi}{2} - \frac{2}{\sqrt{1-a^2}}\tan^{-1}\frac{(1-a)}{(1+a)}\right\}$$

where

$$a = \frac{1-\mu}{\mu}$$

and μ = permeability of the armor wire. This formula is based upon the assumption that the armor wires are in contact with one another along their entire length.

The relation between this ratio and the permeability is shown in Fig. 54.

The effect of the flux in the armor on the total inductance of the cable will depend upon the proportion of the total field of force which is occupied by the armor.

First assume the two cables to be alongside each other with their armor wires touching, and let the permeability of the armor

[1] *Trans. A.I.E.E.*, vol. 28–2, p. 737, 1909, corrected.

wires = 1. Let L_1 be the inductance, calculated by the formula for L on p. 138, but converted to a mile basis.

Let L_2 be the inductance similarly calculated for the space under the armor wires, *i.e.*, using for D in the inductance formula the diameter under the armor wire. Then $L_3 = L_1 - L_2$ will be the inductance due to the space occupied by the armor wires. If, now, the permeability be μ instead of 1, the inductance due to the armor wires will be kL_3.

Now assume the cables to be any distance apart D, and calculate the inductance L_4, neglecting the armor. Subtract L_3 as calculated above and replace by kL_3, or, what is the same, add to L_4 $(k-1)$ times L_3. This gives the inductance L, with the armor.

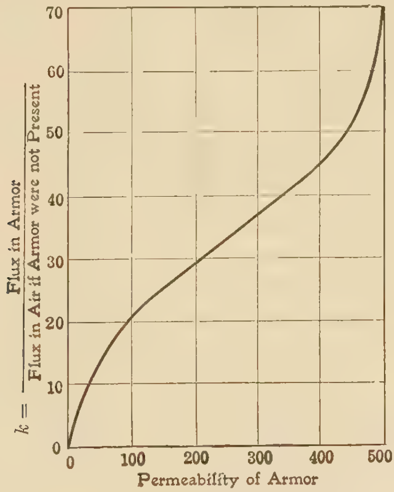

FIG. 54.—Curve for estimation of flux in armor wires of various permeabilities.

For example, if

Diameter over armor	= 1.50 in.	Distance apart	= 3.50
Diameter under armor	= 1.23	Radius of conductor	= 0.186

$$L_1 = 0.0805 + 0.741 \log_{10} \frac{1.5}{0.186} = 0.75$$

$$L_2 = 0.0805 + 0.741 \log_{10} \frac{1.23}{0.186} = 0.69$$

$$L_3 = 0.06$$

$$L_4 = 0.0805 + 0.741 \log_{10} \frac{3.5}{0.186} = 1.02.$$

Let $k = 36$

$L = 1.02 + [35 \times 0.06] = 3.1.$

The inductance should be reduced to about 0.7 of the value thus obtained, to allow for the fact that armor wires do not make perfect contact.

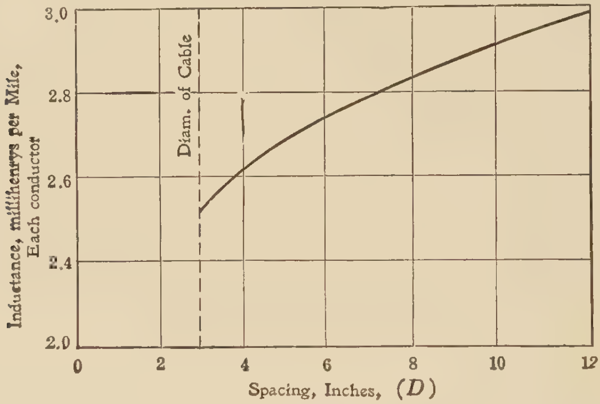

FIG. 55.—Inductance for various cable spacings, the permeability being assumed to be 300.

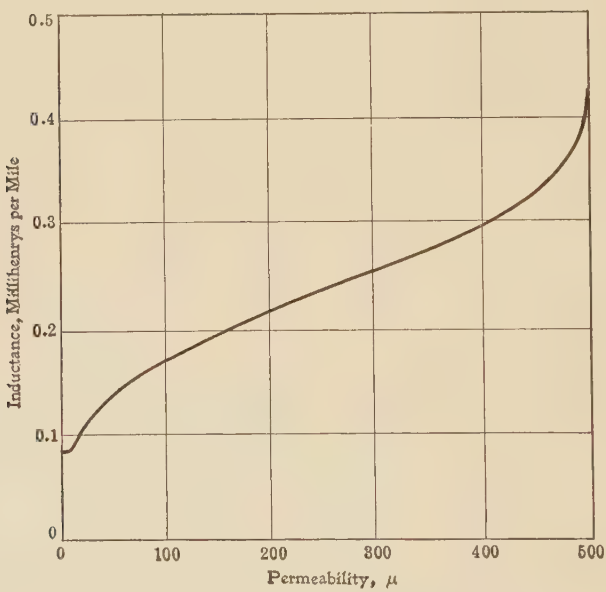

FIG. 56.—Inductance for various permeabilities of armor wire.

In the case of a 350,000-cir. mil cable with $^{34}\!/_{64}$-in. insulation, $\frac{1}{8}$-in. lead, $\frac{1}{8}$-in. jute and No. 6 B.w.g. armor wires, the inductance per cable will be as follows, assuming $\mu = 300$.

Item	6-in. Spacing
Inductance without armor[1]	0.74
Total inductance	2.52
Total inductance, actual (70 per cent of above)	1.76
Ratio of actual inductance to that without armor	2.38
Impedance, ohms per mile	0.914
Impedance, of conductor of corresponding triplex cable, ohms per mile	0.25

[1] Inductances are in millihenrys per mile.

The inductance for various values of spacing is shown in Fig. 55, and for various permeabilities and minimum spacing, in Fig. 56.

It thus appears that the impedance will be three or four times as great as that of a triplex cable, a ratio which would be very serious on long lengths but not serious for short lengths, such as the usual river crossing.

CHAPTER XX

THE PRESENT VOLTAGE LIMITS IN IMPREGNATED-PAPER CABLES

Electric cables have lagged behind other electrical devices in the development of high voltages. The reason has been that the designer of a high-voltage cable is limited by the maximum permissible diameter, which is usually from 3 to 3½ in. This limit is usually imposed by the diameter of the duct, but, even if larger ducts were used (and some cities are using 4- to 4½-in. ducts), the diameter of the cable could not be much over 3½ in. without making the cable too clumsy to install with reasonable ease.

The designers of transformers and other apparatus have not been limited in this way. It would be safe to say that if transformer designers had not been allowed to increase the dimensions of their apparatus beyond the standard of thirty years ago, they would not have progressed very far in raising the voltage limit; yet this is the condition with which cable designers have had to contend. In other words, the designers of most electrical apparatus have been able to use their materials within ordinary limits of electrical stresses, increasing the dimensions whenever it became necessary to carry higher voltages, but keeping the stresses practically unchanged. The designers of cable, on the other hand, have been obliged to keep the dimensions unchanged and have increased the electric stresses. In the case of most electrical apparatus, development has been along the line of utilizing existing knowledge, whereas all research work tending toward the improvement of cables must be in the nature of delving out fresh knowledge of the nature of materials.

As explained in previous chapters, the voltage which a cable can carry is limited by two properties of the insulating materials, the average power factor, which determines the average heating of the insulation, and some unknown property of materials, perhaps a local power factor, which determines failures at high voltages.

The limited diameter and the poor-heat-dissipating quality of ducts make an installed cable a poor dissipator of heat. The heat that a 3-in. cable can dissipate under these conditions is from 0.15 to 0.25 watt per foot per degree Centigrade temperature rise.

Considering the problem of heat dissipation in greater detail, it is found that the heat resistance from conductor to ground of a 25- or 30-kv. triplex cable is made up, approximately, as follows:

	Per Cent
Insulation	82
Sheath emission	8
Sheath to duct wall	3
Duct wall to ground	7
	100

The heat resistivity of the insulation, which is the element in which the greatest room for improvement exists, is as follows:

	Degrees Centigrade per Watt-cm.	Degrees Centigrade per Watt-inch
Impregnated paper	750 to 1200	295 to 455
Varnished cambric	635 to 900	250 to 350
Rubber compound	635 to 900	250 to 350

The great variations observed in each of these materials have been the subject of study by the National Physical Laboratory of Great Britain and numerous other agencies, but no notable progress has yet been recorded in increasing the heat conductivity of insulation.

The emission of heat from sheaths varies from 150 to 180° C. per watt dissipated from each square inch of surface, depending upon the condition of the surface. No systematic attempt has been made to utilize this variation, because of the practical difficulty of preserving any special surface on the lead during the act of drawing in the cable, and while in service.

The problem of the cable designer is, therefore, to transmit through the cable perhaps 20,000 kw., with a loss not exceeding the limited heat-dissipating ability described above.

The energy loss is partly in the conductor and partly in the insulation. Commercial copper has a conductivity of about 100 per cent of the annealed copper standard. There is no better metal available at any price. Any improvement which may occur along this line must be due either to some lucky discovery, or to some research work of a very fundamental character.

The insulation loss, on the other hand, has been the subject of considerable improvement. During the past few years the power factor of impregnated-paper insulation has been reduced from over 20 per cent to less than 2.0 per cent at 85° C. or 1.0 per cent at 60° C.

The dielectric loss, however, depends upon both the power factor and the specific capacity of the insulation, and no progress has been made toward lowering the latter. This is an important matter, as at high voltages the charging current is very large and on long lines may seriously curtail the useful carrying capacity of the cable. Thus, a 45,000-volt line 100 mi. long would not be able to carry much useful current, as nearly all its carrying capacity would be taken up by the charging currents.

The very highest temperature at which an impregnated-paper cable could operate would be limited to about 135° C. by the fact that insulation chars slightly above that temperature, but unfortunately other limitations come into play at much lower temperatures. One of the most serious of these is the permanent expansion of the paper and lead at temperatures above 60° C., which results in the formation of voids in which vapor ionizes. Furthermore, the longitudinal expansion and contraction of cables in ducts leads to abrasion of the sheath. The matter of voltage regulation must also be considered.

This entire matter of temperature limits for cables is the subject of an exhaustive research now under way at the Massachusetts Institute of Technology. This research is being supported by the N.E.L.A. and is under the direction of the Cable Research Committee of that society.

It is interesting to study in greater detail the effect of the power factor upon carrying capacity. Assume a triplex cable, 3 in. in diameter, of a commonly used conductor size, for use on a three-phase system with grounded neutral. Such a size would be 350,000 cir. mils, sector-shaped and about the most effective insulation which could be applied within the diameter limitation would be $^{19}\!/_{64}$ in. on each conductor and $^{7}\!/_{64}$ in. overall.

A formula was given in Chap. X for calculating the effect of dielectric loss upon the carrying capacity of a cable. If the symbol for dielectric loss in this formula be replaced by its equivalent in terms of tension, capacity and power factor, and if the symbol for current be replaced by its equivalent in terms of kilowatts, capacity and tension, the following formula will be

obtained expressing the carrying capacity in kilowatts in terms of the power factor and tension.

$$W = \frac{191}{\sqrt{r}} E \sqrt{\frac{T}{R} - 0.0159E^2CP} \qquad (1)$$

where W = power carried by cable, kilowatts.
r = electrical resistance, ohms per 1,000 ft. of conductor.
R = heat resistance, degrees Centigrade per watt-inch.
E = tension between conductors, kilowatts.
C = capacity between any two conductors, marofarads per mile, as if the specific capacity were unity.
P = power factor of insulation as a fraction.
T = temperature rise, degrees Centigrade.

It will be noted that E occurs in two places in the formula, first, so that an increase in it will increase W, and then so that it will decrease W. There is, therefore, a certain value of E which makes W a maximum and this occurs when

$$E = \sqrt{\frac{T}{0.0318CPR}}. \qquad (2)$$

Take the following values for the cable, assuming the specific capacity to be 4.

T = 20° C. (= 60° final, 40° ambient).
C = 0.05.
R = 163.
r = 0.035 at 60° C.
P = 0.1.

Then a graph of Eq. (1) will be as shown in Fig. 57, which clearly shows the maximum point referred to above. This maximum point occurs at about 28 kv. for the power factor assumed. For lower power factors, the voltage corresponding to the maximum carrying capacity will increase and for higher power factors it will decrease, as shown in Fig. 58.

Most of the old resin-oil cables had power factors as high as 25 per cent at 60° and in this case the maximum carrying capacity in kilowatts would be attained at less than 18 kv. per conductor. At 40 per cent power factor, which was not at all unusual in the cables of twenty years ago, the maximum carrying capacity occurs at 14 kv. It is, therefore, very doubtful whether the early high-voltage installations could be justified in the light of present knowledge.

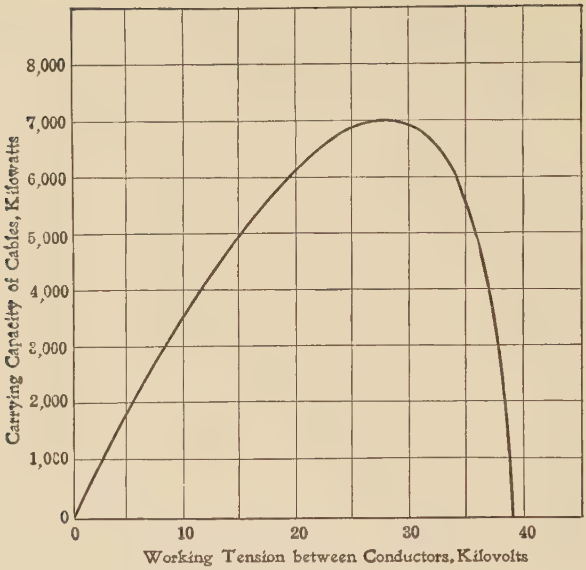

FIG. 57.—Typical curve showing relation between working tension and power carrying capacity.

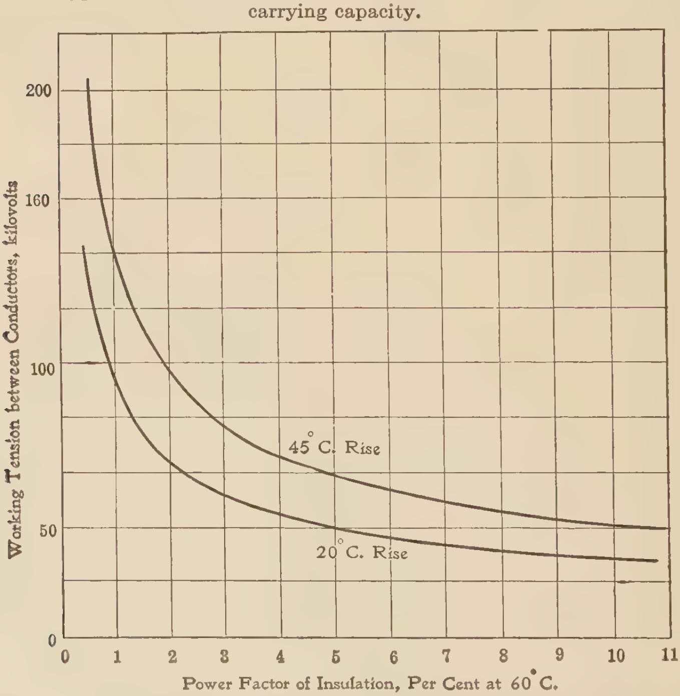

FIG. 58.—Voltage for maximum power carrying capacity as related to power factor of the dielectric.

When all the problems relating to temperature have been solved, there remains the problem of dielectric strength. In other words, since power factors are below 2 per cent at 60° C., there is no reason, as far as average heating is concerned, why tensions as high as 60 kv. cannot be used.

At the present time, the breakdown voltage of solid or semi-solid insulation in relation to its thickness, and the electric field distribution within it, is not clearly understood. This problem has been solved for air and oil, but not for the materials used as cable insulation. Until it is solved, the voltage which a cable will stand cannot be accurately predetermined from tests on samples of the insulation. This subject was discussed at greater length in Chap. XIII.

This matter of dielectric strength is now the crux of the problem. Triplex cables are being operated at 33,000 volts, and single-conductor cables at 38,000 volts to ground (66,000 between conductors). The heating due to dielectric loss is negligible, and the cables stand the factory tests at two and one-half times the working voltage without trouble. The number of operating failures, however, has been considerably greater than in lower voltage cables, and operating engineers are loath to go to cables of higher voltages until the present ones have become more reliable. The division of responsibility for these failures between cable trouble and abnormal circuit conditions, has not been determined.

One of the most important practical manufacturing limitation at the present time is the difficulty of obtaining high vacua in the large tank systems which are necessary in American cable plants. After that comes the difficulty of obtaining the right quality of oil for impregnating compound. The oil refineries seem to be unable to produce a steady supply of oil having the desired electrical and chemical properties. Cable manufacturers who have adequate oil specifications only occasionally receive oil which complies with all the requirements. The result of this is a wide variation of cable quality, especially dielectric strength.

Another limitation is the imposition of manila-rope paper by customers' specifications. It is known that better results can be obtained with wood or mixed-fiber papers.

It is possible that all dielectric failures result from local cumulative heating, although this is by no means certain. If this is the case, there is an important class of failures, which is due not

to the direct application of the voltage but to some kind of secondary reaction whereby either local internal resonance effects are set up, or voltages are superimposed in some other way.

Having incorrectly assumed that the voltage which a cable will carry depends upon the maximum stress in the insulation, various engineers have attempted to equalize the stress throughout the thickness of insulation, with the idea of doing away with high stresses.

Two methods have been suggested, one involving the use of intersheaths, *i.e.*, metallic layers interspersed through the insulation and connected to equidistant points of an autotransformer, and the other based on the use of successive layers of insulation differing in specific capacity.

The chief objections to the former method are given as follows by Clark and Shanklin.[1]

(*a*) The intersheath must necessarily be of flimsy construction and there is danger of damaging it or even breaking its continuity during transportation and installation. High local potentials would concentrate at this point, resulting in failure.

(*b*) The length of line would be very limited, as the intersheath could not carry the heavy charging current in long lines.

(*c*) This method is based on the supposition that it is desirable to stress equally the whole insulation cross-section. Actually, it is not desirable, because of the high dielectric loss involved.

(*d*) Weak spots in the different layers would be lined up over the whole length. Failure of one layer would throw full potential on the others, also the short-circuit current might fuse the intersheath at some point far distant from the original point of failure.

The latter scheme has been deemed worthy of trial on a larger scale, and is therefore considered below in greater detail.

The general idea is that, when two insulating materials are placed in series in an electric field, the potential gradients in them will vary inversely as their specific capacities. Hence if, in a single-conductor cable, a material of high specific capacity be used near the conductor, where the field is intense, and a material of low specific capacity be used near the sheath, where the field is comparatively weak, the potential gradient near the conductor will be decreased and that near the sheath increased.

Grading is found to be unsuccessful for the following reasons:

[1] *Jour. A.I.E.E.*, vol. 38–1, p. 924, 1919.

1. The breakdown voltage (on test) does not depend upon the maximum stress, at least in impregnated-paper and varnished-cambric insulation.

2. It happens that cable insulations of high specific capacity have low dielectric strength, so that they cannot be advantageously used where the electric field is intense.

3. No insulation except impregnated paper has sufficiently low dielectric loss for high-voltage cables.

There is very little difference in the specific capacities of different samples of materials of the same class, so that it is necessary to use different materials in order to obtain grading. The only materials used in American practice are the following:

Material	Specific Capacity
Rubber compounds	4.5 to 6.0
Varnished cambric	3.5 to 5.0
Impregnated paper	3.0 to 4.0

The dielectric strengths cannot be stated so simply, but that of impregnated paper is highest, followed by varnished cambric, with rubber last. This is true for any period of application of the voltage, but the discrepancy is increasingly great as the time of application is increased, due to the differences in power factors of these materials.

Clark and Shanklin say that:

> It is much better to have the insulation a homogeneous compact mass of impregnated paper and aim towards a uniformly high-grade product with low temperature coefficient and dielectric loss.

Graded cable (No. 4 A. w. g.) made with $\frac{8}{64}$ in. of 30 per cent heavy rubber insulation next to the conductor, covered with $\frac{4}{64}$ in. of varnished cambric and $\frac{4}{64}$ in. of impregnated paper and a lead sheath, broke down at the same voltage as a cable with $\frac{16}{64}$ in. of impregnated-paper insulation, when tested according to A.I.E.E. Standards.

It is significant that none of the very high-voltage cables now operating, or contemplated, is graded.

At the present time, there is being projected a three-cable feeder for 132,000 volts between phases, each cable being designed for 76,000 volts. Some experimental cables for this line have already been made. The highest voltage lines in America are those in Cleveland, Ohio, which are three-cable circuits with 66,000 volts between phases, and the United Electric

Light & Power Company in Westchester County, New York, which has 45,000 volts between phases.

The highest voltage lines in Europe are those in Paris, France and Barcelona, Spain, which are operating at 60,000 and 50,000 volts, respectively.

Two tables are appended, one showing the highest voltage triplex and the other the highest voltage single-conductor cables now in operation, or contemplated, in Europe and America.

European cable manufacturers have had an advantage over the Americans which has enabled them to establish excellent records with certain extra-high-voltage cables, namely that their cables are generally armored and laid in the ground without the injurious pulling and bending to which American cables are subjected when drawn into ducts. The published records of the cables are, unfortunately, often quite unreliable.

Data on Extra-high-voltage Cables, Single-conductor, on Three-phase Circuits

Location	Date	Normal operating voltage	Size of conductors, circ. mils	Thickness of insulation, inches	Maximum dielectric stress, kilovolts per centimeter
Barcelona	1917	50,000	99,000	0.552	45.1
Florence	1916	40,000	148,000	1.18	22.3
Turin	1916	38,000	138,000	0.67	28.7
Turin	1917	38,000	99,000	0.646	31.4
Paris	1922	60,000	295,000	0.538	40.5
Westchester County, N. Y.	1922	45,000	500,000	0.625	27.0
Lille	....	45,000	....	0.416	....
Cleveland, Ohio	1924	66,000	500,000	0.940	31.0
Columbus, Ohio	1924	40,000	500,000	0.625	25.0

DATA ON EXTRA-HIGH-VOLTAGE CABLES, THREE-CONDUCTOR

Location	Date	Normal operating voltage	Size of conductor, circ. mils.	Thickness of insulation		Maximum dielectric stress between conductor, kilovolts per centimeter
				Conductor, inches	Belt, inches	
St. Paul	1900	25,000	66,400	0.281	0.125	32.0
Berlin	1911	33,000	99,000	0.288	0.288	41.6
Rome	1913	30,000	39,500	0.473	.....	47.7
Caen	1914	33,000	79,000	0.216	0.216	47.3
Rome	1919	30,000	49,400	0.630	.....	38.7
Naples	1919	32,000	237,000	0.590	.....	30.6
Rome	1920	30,000	59,000	0.552	.....	39.8
Chicago	1921	33,000	350,000	0.297	0.11	29.4
Manchester	1921	33,000	382,000	0.25	0.25	32.3
Birmingham	1921	33,000	255,000	0.25	0.25	34.6
Newcastle-on-Tyne		44,000	191,000	0.375	0.175	
Erith (England)	1921	33,000	320,000	0.25	0.25	33.6
Clyde Valley	....	33,000	250,000	0.256	0.138	34.4
St. Louis	1924	33,000	350,000	0.359	0.141	26.0

The Chicago and St. Louis cables have sector-shaped conductors; all others are round. Dielectric stresses calculated according to Davis and Simon (*Journal, A.I.E.E.*, Jan., 1921). The numerous American cables operating at voltages from 25,000 to 27,000, are omitted except in the case of the St. Paul cable which is given for its historical importance. A 66,000 volt triplex cable has been installed in Holland by and English manufacturer, but has not been in regular operation, (October, 1924) long enough to judge its practicability.

CHAPTER XXI

WIRES AND CABLES FOR MISCELLANEOUS PURPOSES

The general uses of the various types of wires and cables have been indicated in the preceding chapters, but a number of industries require wires and cables of more or less special character and this chapter deals exclusively with them.

BUILDINGS

Classes of Wiring.—Wires may be installed in buildings either in conduits or raceways or on porcelain knobs.

If the wiring must be enclosed, two systems are available:

1. Concealed-conduit wiring.
2. Concealed knob-and-tube wiring.

If the wiring may be exposed, three systems are available:

1. Open-conduit wiring.
2. Metal-raceway wiring.
3. Exposed knob-and-cleat wiring.

In general, the above systems are used as follows:

Concealed-conduit Wiring.—Public buildings, office buildings, hotels, apartment houses and high-class residences.

Concealed or Knob-and-tube Wiring.—Inexpensive frame houses, where it is not a serious drawback that walls and floors must be opened to make repairs.

Open-conduit Wiring.—High-class factories, power stations, warehouses.

Metal-raceway Wiring.—Office buildings, factories, warehouses and garages.

Exposed Knob-and-cleat Wiring.—Factories and mills.

Wiring Rules.—The following rules are abstracted from the Regulations of the National Board of Fire Underwriters and must be followed if it is desired to insure the building against fire.

Wires must not be of smaller sizes than No. 14 A. w. g., except as allowed for fixture wire and cords.

Wires must be so spliced or joined as to be both mechanically and electrically secure without solder. The joints must then

be soldered unless made with some sort of approved splicing device and covered with insulation equal to that on the conductors.

Stranded conductors, except in flexible cords, must be soldered before being fastened under clamps or binding screws. All conductors, whether solid or stranded, larger than No. 8 A. w. g. must be soldered into lugs for all terminal connections, except where an approved solderless terminal connector is used.

The neutral conductor of all three-wire circuits and one conductor of all two-wire circuits must have an identifying insulating covering, readily distinguishing it from other wires. This wire must be run without transposition throughout the entire installation and be connected at all fittings to properly identified terminals in order to preserve its continuity.

Where entering cabinets, cut-out boxes or junction boxes, wires must be either in conduit, armor or metal raceways or protected by non-combustible, non-absorptive insulating bushings which fit tightly the holes in the box or cabinet and are well secured in place. The wires should completely fill the holes in the bushings so as to keep out dust, tape being used to build up the wires if necessary. For concealed knob or tube work or for open work in dry places, an approved flexible tube will be accepted instead of bushings, provided it extends from the last porcelain support into a wooden cabinet or is secured to a metal cabinet, cut-out box, junction or switch box by an approved fitting.

Wires must not be laid in plaster or cement, and must never be fastened with staples.

Twin wires (flat) must never be used except in conduits or where flexible conductors are necessary.

SHIPS

The wiring of ships presents certain definite conditions because of the great amount of moisture in sea air and the condensation which takes place on the inside of the shell and even on the bulkheads of steel ships, especially in cool climates.

Formerly, vessels were wired in much the same way as buildings, but this is not satisfactory because dampness causes the braided coverings and rubber-insulating compound to deteriorate rapidly. About the only way in which braided wires could be adequately protected mechanically was by running them through conduit, but the warm air circulating through these conduits

became chilled by contact with the cold metal work and the moisture condensed, causing the interior to be continuously damp, the moisture collecting, by gravity and capillary action, along the braids, in panel boxes, junction boxes, etc., often causing short circuits and always causing corrosion of metal and rotting of insulation.

Conduits on the decks of vessels, where they are exposed to rain and spray, will collect dampness directly without condensation unless absolutely watertight. It is almost impossible to maintain the joints in conduits watertight when the runs are of any length, because of the pitching and rolling of the ship and the vibration from the engines.

The make-up of the conductors and the method of installation as adopted by the Marine Committee of the A.I.E.E. are outlined below.

In the first place, all conduits are discarded except very short lengths where the conductors pass through decks or bulkheads (transverse partitions). This effects a great saving of material.

The next requirement is a flexible moistureproof conductor or cable with sufficient mechanical protection to make good the omission of conduit.

Suitable flexibility has been obtained by using stranded conductors. These conductors have the advantage of being easily connected and of being much less liable to break, due to the vibration and movements of the ship at sea.

Moistureproofness is secured by using a lead sheath. This precaution is necessary only where there is contact with moisture on the decks or within the ship below the water line, where the cold steel work "sweats." The lead sheath is not necessary within the ship above the water line, but if conduits are used which extend from warm places to cool places the inside of the whole run would be damp from the condensation of moisture in the air circulating through the pipe. The Navy Department, justifiably wishing to have the greatest possible reliability of service under all conditions when in action, specifies the lead covering for all locations, but the Marine Code does not require it for merchant vessels for interior locations above the watertight deck.

Mechanical protection is secured by an outside covering consisting of a galvanized steel-wire braid, known as "basket weave armor," which has been drawn through a bath of hot asphaltum

in the factory, to fill in all interstices between wires, and also to coat the outside, which is also painted over with a heavy lead paint after installation and at frequent intervals during service as protection against corrosion.

The general make-up of wires and cables complying with the requirements of the Marine Code is, therefore, as follows:

Number of conductors, one or more as specified.

Range of sizes, 7 to 0.025 in. and upwards, soft copper, stranded, tinned.

Insulation, 30 per cent hevea rubber compound.

Covering over insulation, one rubber-filled tape.

Grouping of conductors, twisted.

Fillers, paraffined jute. (The filler is, of course, omitted if there is only one conductor.)

Covering over jute, one rubber-filled tape. (This is omitted if there is but one conductor, but the succeeding elements are included just the same.)

Waterproof covering, lead sheath.

Covering over lead, acid-free compound and tape, half-lapped.

Armor, galvanized soft-steel-wire braid (basket-weave).

Covering over armor, single coat gray paint or asphaltum.

Of course, cables made up in this way are more expensive than ordinary Code wire, but the material and labor saved by the omission of conduits more than make up for the cost.

The general method of wiring a ship is to run a large number of separate cables, comparatively small, from the switchboard to each of the many distribution panels located at various points on each deck. The cables are run in the different directions necessary, in groups, much as raceway wiring without the raceway. At the switchboard end the cables run from the switches out toward their various distribution points, and are made up into neat form, occupying only a small space. This method of closely bunching numbers of cables into forms would be impracticable with conduits, and the saving of space on shipboard is of prime importance.

A separate armored cable is run from the distribution panel to each outlet, in so far as practical, in order to reduce to a minimum or, if possible, to eliminate entirely all junction boxes.

COAL MINES

Cables are used in coal mines for furnishing power to electric locomotives and coal-cutting machines.

Electric locomotives are run by an overhead trolley along the main galleries, but when the locomotives reach new cuttings power is obtained from the trolley by a flexible cable, which is ordinarily rolled up on a drum on the locomotive and unwinds as the locomotive proceeds into the new section. As the locomotive returns, the cable winds up on the drum.

Coal-cutting machines are similarly fed from the main galleries by means of flexible cables which lie along the floor and, like the locomotives cables, are subjected to rough usage.

Both types of cables are likely to be run over by cars and their lives are, therefore, very short. It has been the custom to make the cables as cheaply as possible and replace them at frequent intervals. The present tendency is to use expensive cables having longer life. Both mining locomotives and coal-cutting machine cables are usually of the two-conductor type, although single-conductor cables are occasionally used by locomotives. The older type is rubber-insulated with extra-tightly woven cotton braids for mechanical protection. The most recent type is also rubber-insulated, but, instead of protecting braids, a tough rubber sheath is used without any fibrous covering.

In some mines, concentric cable, and in others twin (flat) cable, is preferred. Where the rubber sheath is used, the two conductors are usually twisted together. The range of size is from Nos. 2 to 8 A. w. g. and the conductor usually consists of 49 strands.

Concentric cable has the advantage of smaller diameter, and a greater length can therefore be carried on a locomotive reel.

Where braids are used, it is most important that the braids should be very tight, as a loose braid will slip, form into lumps and stick at the gathering mechanism of the locomotive.

Cables are sometimes run into mines through boreholes, which may be several hundred feet deep. Two constructions have been adopted, one an armored cable, with one of the armor wires left out and equipped with wire seizings every few feet. The omission of one of the armor wires permits the remaining ones to grip the insulation tightly without any danger of an arch effect. The steel armor wires carry the stress, the cable being supported at the top of the borehole by the armor wires. The other type of cable is lead-covered, rubber-insulated and is supported between a pair of steel messenger cables, to which it is attached by means of a double figure 8 wrapping of wire every 10 ft.

POWER STATIONS

The peculiarity of power-station wiring is that a large number of short lengths of cable are required, many of them operating at high voltages.

Impregnated paper seems to be impracticable because of the numerous potheads that would be required at the ends. Rubber insulation is undesirable for higher voltages, because ionization destroys the rubber. Varnished cambric is, therefore, the principal insulation used. It is usual to cover the varnished cambric with a flameproof or asbestos braid.

RAILWAY SIGNALS

Large quantities of wire are used for operating electric signals, either manual or automatic. Because of the importance of these wires from the standpoint of safety to passengers, the greatest care is taken to use reliable insulation. The chief peculiarity of signal wire is, therefore, the high quality of the insulation, which is practically always rubber because of the small size of the conductors. The usual finish of signal wire is a rubber-filled cotton tape and a single-saturated braid, over the rubber insulation. Cables are made with various numbers of conductors, depending upon the number of signals to be operated. Such signal wires are usually installed in wooden trunking at the side of the tracks.

In recent years this construction has been replaced in some places by multiple-conductor "park cable," *i.e.*, band-armored cable, which is laid in the ground at a depth of about 2 ft.

INDUSTRIAL PLANTS WHERE THERE IS MUCH MOISTURE

Abattoirs, ice plants, shipyards and other places where moisture is prevalent should be wired with rubber-insulated, lead-covered wires and cables, as rubber insulation deteriorates rapidly in contact with moisture.

CHAPTER XXII

ELECTROLYSIS

The word electrolysis, as applied to cable operation, refers to the corrosion of sheaths or of armor wire, due to stray currents in the ground. When a direct current is passed through a solution of a metallic salt, the salt is decomposed into an acid and a metal or oxide of a metal. The acid is deposited at the positive pole and the metal or metallic oxide at the negative pole. Hence, if a stray current enters a lead sheath from the ground, at any point, metallic salts in solution in the ground will be decomposed and metallic oxides will be deposited on or near the surface of the sheath. These oxides are usually entirely harmless. If lime is liberated, however, it is likely to attack lead sheaths.

If, however, the current leaves the sheath at another point to enter the earth, earth salts will be decomposed at that point, but acids will be deposited on the surface of the sheath, causing it to corrode and often to become pitted and eventually pierced with holes.

The stray currents which do this damage come usually from the track rails of street railways.

Electrolysis can be prevented by any of the following procedures:

1. By the railway company keeping the voltage drop in its rails so low that but little current will leak into the earth.
2. By keeping the cables far enough away from the railway tracks to be outside the danger zone.
3. By attaching drainage wires to the sheaths where the current shows a tendency to leave the sheaths, such drainage wires being connected with the negative bus of the railway substation. This plan is not always successful, especially if the leakage path from cable sheath to ground has a low resistance, because in that case the wire will only take a part of the injurious leakage current.

It would be desirable to have a type of sheath or armor immune from electrolysis. In the case of park cables the asphalted jute over the armor exercises considerable protective effect, but is not to be relied upon.

The following is quoted from the Report of the American Committee on Electrolysis (1921):

From an electrolysis standpoint, it is usually necessary to treat lead-sheath cables as distinct from other underground structures, due to the fact that lead is appreciably more susceptible to corrosion from stray current than iron, and also because different measures are usually applied to the protection of lead-sheath cables than to other underground metallic structures. One ampere flowing steadily for a year will carry into solution about 20 lb. of iron or about 74 lb. of lead. This high electrochemical equivalent of lead and the thin walls ordinarily used for cable sheaths require that unusual care be exercised in their protection.

In the Bell Telephone System precautions are taken to avoid contact between its lead-sheathed cables and other underground structures, such as foreign cables, rails, steel bridges, gas or water piping systems, and the metallic structure of steel-frame buildings. Where it is necessary that cables cross a bridge structure, this is frequently accomplished in creosoted-wood ducts. Occasionally, however, iron pipes are used to conduct cables across a steel bridge, but where this is done, these pipes are supported so that they are insulated from the metal work of the bridge.

Cable sheaths cannot be said to be insulated from earth, even when installed in non-conducting duct material, but, as compared with pipes which are laid directly in the earth, their resistance to ground is generally very high. Unless surrounded with mud or water, cable sheaths usually make a line contact with the duct walls, whereas pipes make a surface contact of much greater area.

The study of the insulation of cable sheaths from earth therefore resolves itself into a study of suitable conduit construction methods, since experience has demonstrated the failure of any sort of wrappings, dips or coatings to afford protection of any value from electrolysis. Indeed, wrappings, dips and coatings have been shown to be distinctly harmful where pipes or cables are positive to the earth, since they tend to localize the discharge of current and thus to accelerate failures.

The experience of the Bell Telephone System has demonstrated that multiple and single vitrified-clay duct and creosoted-wood duct are equally good as duct material from the standpoint of electrolysis, their choice in specific cases being a question of supply and cost. Iron pipe is occasionally used, but, due to its cost, only when necessary in avoiding obstructions.

When iron pipe is used, it is so laid that there will be no contact between it and the trolley rails, steel bridges, water pipes, gas pipes or other underground structures or the metal work of buildings. When iron pipes must be laid as conduit so close to rails or other grounded metallic structures that a separation of at least 1 ft. of earth cannot be

obtained, the pipes are separated from the rails or other grounded metallic structures by a layer of concrete or creosoted plank. Three-inch vitrified sewer tile with cement joints is now being commonly used for laterals to poles or building connections.

In good conduit construction the necessity is recognized of rendering the joints between lengths of duct material sufficiently tight to prevent the infiltration of dirt and silt and also to maintain a sufficient slope to the conduit to insure good drainage toward manholes, the manholes in turn being drained by sewer connections or to sumps. Particular care is exercised to prevent dips or pockets in conduit runs where moisture might collect. It is the practice to rack cables in manholes, a free space of 12 in. being maintained between the lowest cable and the manhole floor. The cables are in metallic contact with the metal hanger, which, in turn, may be in contact with or built into the manhole wall, experience having indicated that no appreciable increase in cable resistance to earth is obtained by insulating the cables at these points with porcelain or other insulating material.

Where lateral cables enter buildings, it is the usual practice in the Bell System to avoid all contact between the cable and the metal structures of buildings, and, wherever this is impracticable, the continuity of sheaths on the entering cables is broken by an insulating joint.

Occasionally conduit runs must be built through swampy ground or along sections of the coast where the conduit is permanently below sea level. Where such conditions are encountered, no method is practically possible for insulating cable sheaths from earth and such insulation is not attempted. Such locations are frequently extremely troublesome from the electrolysis standpoint, and therefore special precautions have to be taken.

The practice in conduit construction for light and power cables is somewhat different from that used for signal cables, because in the former it is necessary to provide for troubles originating within the cables and for the dissipation of the heat losses of the cable. The most common types of duct material used are single-duct vitrified tile, multiple-duct vitrified tile, fiber conduit and stone conduit. Iron pipe is frequently used for short laterals to buildings and for cable pole connections, and occasionally where, on account of lack of space, other types cannot be installed. It is a common practice to install a 3-in. concrete envelope entirely surrounding all types of power conduits. Multiple conduit made up of single-duct tile is laid with staggered joints and in the case of the fiber and stone conduit the ducts are separated by an inch or more of concrete. Fiber duct is generally considered as a mold for the concrete, the latter being depended upon for strength and for the separation of the cables in the several ducts.

The waterproofing of underground conduits for the purpose of excluding moisture and improving the conditions regarding electrolysis was

tried a number of years ago, but it was very expensive and found to be quite useless unless the manholes also could be waterproofed, and this did not appear to be practicable.

The reports of the effect of the different types of duct on electrolysis conditions vary considerably, but this is probably due to the nature of the soil in which the conduits are located, the amount of moisture in the soil and the character of the paving under which the conduits are installed. In those locations where the conduit is located in flat country with poor drainage and with the natural water level only slightly below the level of the conduits, the effect of the dirt and moisture in the ducts and of the dampness in the surrounding earth is to lower the resistance of the cables to earth so that this value is not materially greater than it would be if they were installed directly in the earth. In other locations where the surface of the ground is hilly or sufficiently undulating to afford good drainage facilities, the cables installed in ducts with a concrete envelope are fairly well insulated from the earth.

Although iron pipe is not generally used in line conduits, it is frequently necessary to employ it for laterals from manholes to poles and buildings, in order to avoid obstructions or to comply with requirements. If used as conduits for drained cable systems, iron laterals will increase the danger to gas and water service pipes which they cross. They also lower the resistance between the earth and cable sheaths which they contain, and thereby enable the cables to pick up larger amounts of stray current than they otherwise would.

In order to afford the return current a metallic path to the station in case of the failure of the cable, it is the standard practice with many companies to connect the lead sheaths of all their cables in every manhole. This serves also to prevent serious differences in potential between the lead sheaths of cables in the same conduit at the time of a burnout and the resulting damage to lead sheaths in adjacent ducts which would otherwise occur.

Where metal racks are used in manholes it is a frequent practice to insulate the cables from such racks, this being done to prevent damage from electrolysis as well as to prevent damage in case of a burnout of one of the adjacent cables.

Some light and power companies have used insulating joints for protecting their cables from electrolysis. In some cases each section was connected to a ground pipe or plate under the floor of the manhole. If the conditions were favorable for electrolytic action, these ground plates or pipes served merely as auxiliary anodes and would be destroyed by electrolytic action in the course of a few years, thus rendering them ineffective except at a considerable annual expense for maintenance. Partly for this reason, but more because of the general adoption of cable drainage as a method of electrolysis mitigation, the use of insulating

joints for protecting lead-covered cables for light and power purposes has been practically abandoned in this country.

As the drainage of cables required continuous lead sheaths, insulating joints are not now ordinarily used in cable systems. With drainage it is also desirable that the several cables in any duct system be bonded together in the manholes, so that all cables may be equally drained and also so that in case of a failure of one cable the current through the fault to the sheath can find a continuous metallic return path to the station. If the insulation fails on a cable with an isolated lead sheath, the potential of the sheath will become approximately that of the conductor and destructive arcing may occur at the insulating joints, and, in addition, holes will be burned in the lead sheaths of the cable where it is in accidental contact with other cables or where it rests on metal cable racks or supports in manholes.[1] Where insulating joints are used, it is therefore quite necessary to ground each section of the sheath.

Under special conditions insulating joints can sometimes be used to advantage in protecting cables from electrolysis, as, for example, when the cables are remote from any railway tracks or negative return circuit to which they can be drained, or where a cable system which is not drained can be prevented from collecting stray current at points of intersection with railway tracks by their use.

Another situation sometimes requiring insulating joints in order to prevent cables from picking up excessive current, or to prevent arcing, is to be found where they make contact with a steel bridge or are otherwise brought into intimate contact with the earth. Under such conditions the section making contact can be isolated by the use of insulating joints and continuity of the system maintained by bonding around the section so isolated. Such conditions as these, however, are comparatively rare.

Insulating joints in lead sheaths are not only expensive but represent points of discontinuity which may give rise to various troubles and are usually avoided in practice except under such unusual conditions as are here mentioned.

[1] Such arcing may establish surges destructive to the insulation (W.A.D.M.).

CHAPTER XXIII

SPECIFICATIONS AND STANDARDS

Fundamental standards covering nomenclature, methods of test, etc., were established in 1914 by the A.I.E.E. and have been enlarged and revised at frequent intervals since that date.

In 1920 the Underground Systems Committee of the N.E.L.A., in collaboration with the Transmission and Distribution Committee of the A.I.E.E., published detailed specifications for use in purchasing impregnated-paper cables.

A committee was created, in 1921, under the auspices of the American Engineering Standards Committee, and sponsored by the twelve national organizations most interested in wire and cable standards, whose function is to coordinate all existing wire and cable specifications and supply whatever deficiencies may exist. This committee is taking the Standards of the A.I.E.E. and the specifications of the A.S.T.M., A.R.E.A. and N.E.L.A. as the basic material for its work, and will, in due course, issue specifications which, it is hoped, will supersede existing ones.

The general practice in America is to specify the size of conductor, thickness of insulation and lead, and to require certain tests to be made which will ensure that the materials are of good quality. Many European purchasers prefer to specify merely the working conditions and operating requirements, allowing the cable manufacturers to propose their own designs. The latter system has the advantage of enabling progressive manufacturers to capitalize their skill, but it also permits the manufacturer with the least appreciation of practical operating conditions to impose rash practices upon the customer, who is not usually in a position to gage the practical operating knowledge of the manufacturer.

It is probably better, in American practice, to adhere to the present system which, after all, the European system must eventually resolve itself into, due to the improbability of one manufacturer or group of manufacturers keeping permanently ahead of the others.

The art of specification writing is not only of importance in assisting the purchaser to obtain a product of the desired quality, but, when used with intelligence and discretion, has proved itself a powerful influence in accelerating the progress of the art of cable making.

There is an important difference between cable making and most other manufacturing processes involving large masses of material, namely, that in cable making every part of the product must conform to a high standard of perfection. A blowhole in a motor field is not a matter of concern; a pinhole in a cable sheath or insulation makes the cable useless. In most manufactured products dimensional accuracy is needed only in parts which must fit together; in cables, dimensional accuracy is required regardless of fit. A change of materials or processes so slight as to have no consequence in most manufacturing might be fatal to a cable.

This peculiarity of cable making has the effect of making the manufacturers conservative and puts a brake on progress. A progressive, conscientiously written specification will help to lift the manufacturer out of his rut without putting him at a disadvantage because his competitors have to work to the same specification.

Specification writers are likely to stress some favorite quality so strongly that the manufacturers are obliged to sacrifice other less stringently guarded qualities in order that they may meet the specification.[1] Furthermore, the requirement that a large number of tests be made before shipment interferes very materially with deliveries, by congesting the testing departments of the factories. Specification writing is, therefore, a matter which requires experience, knowledge and mature judgment. It is safer to rely on the joint wisdom of a representative committee.

[1] Insistance upon the use of manila rope paper, stringent dimensional requirements and the demand for unnecessary flexibility have concentrated attention on the mechanical qualities of paper to the neglect of electrical properties.

APPENDIX I

DEFINITIONS

Wire.—A wire is a slender rod or filament of drawn metal.

The definition restricts the term to what would ordinarily be understood by the term "solid wire." In the definition, the word "slender" is used in the sense that the length is great in comparison with the diameter. If a wire is covered with insulation, it is properly called an insulated wire; while primarily the term "wire" refers to the metal, nevertheless, when the context shows that the wire is insulated, the term "wire" will be understood to include the insulation.

Conductor.—A conductor is a wire or combination of wires not insulated from one another, suitable for carrying a single electric current.

The term "conductor" does not include a combination of conductors insulated from one another, which would be suitable for carrying several different electric currents. Rolled conductors (such as busbars) are, of course, conductors, but are not considered under the terminology here given.

Stranded Conductor.—A stranded conductor is a conductor composed of a group of wires, or of any combination of groups of wires.

The wires in a stranded conductor are usually twisted or braided together.

Strand.—A strand is one of the wires, or groups of wires, of any stranded conductor.

Unfortunately, many people refer to a bare cable as a strand, a practice which causes much confusion.

Cable.—A cable is either a stranded conductor (single-conductor cable), or a combination of conductors insulated from one another (multiple-conductor cable).

The first kind of cable is a single conductor, while the second kind is a group of several conductors. The component conductors of the second type may be either solid or stranded, and may or may not have a common insulating covering. The term "cable" is applied by some manufacturers to a solid wire heavily insulated and lead-covered; this usage arises from the manner of the insulation, but such a conductor is not included under this definition of "cable." The term "cable" is a general one, and in practice it is usually applied only to the larger sizes. A small cable is called a "stranded wire" or a "cord," both of which are defined below. Cables may be bare or insulated, and the latter may be armored with lead, or with steel wires or bands.

Stranded Wire.—A stranded wire is a group of small wires, used as a single wire.

A wire has been defined as a slender rod or filament of drawn metal. If such a filament is subdivided into several smaller filaments or strands, and is used as a single wire, it is called a "stranded wire." There is no sharp dividing line of size between a "stranded wire" and a "cable." If used as

a wire, for example, in winding inductance coils or magnets, it is called a stranded wire and not a cable. If it is substantially insulated, it is called a "cord," defined below.

Cord.—A cord is a small cable, very flexible and substantially insulated to withstand wear.

There is no sharp dividing line in respect to size between a "cord" and a "cable," and likewise no sharp dividing line in respect to the character of insulation between a "cord" and a "stranded wire." Rubber is used as the insulating material for many classes of cords.

Concentric Strand.—A concentric strand is a strand composed of a central core surrounded by one or more layers of helically laid wires or groups of wires.

Concentric-lay Cable.—A concentric-lay cable is a single-conductor cable composed of a central core surrounded by one or more layers of helically laid wires.

Rope-lay Cable.—A rope-lay cable is a single-conductor cable composed of a central core surrounded by one or more layers of helically laid groups of wires.

This kind of cable differs from the preceding in that the main strands are themselves stranded.

N-conductor Cable.—An N-conductor cable is a combination of N conductors insulated from one another.

It is not intended that the name as here given be actually used. One would, instead, speak of a "three-conductor cable," a "twelve-conductor cable," etc. In referring to the general case, one may speak of a multiple-conductor cable.

N-conductor Concentric Cable.—An N-conductor concentric cable is a cable composed of an insulated central conductor with (N-1) tubular stranded conductors laid over it concentrically and separated by layers of insulation.

This type of cable usually has only two or three conductors. Such cables are used particularly for alternating currents. The remark on the expression "N-conductor," in the preceding definition, also applies here.

Duplex Cable.—A duplex cable is a cable composed of two insulated stranded conductors twisted together.

They may or may not have a common insulating covering. The term "duplex" is used by many people to designate flat, two-conductor cables, the proper word for which is "twin." Others use the word "duplex" to designate any two-conductor cable. The best way out of the difficulty is to distinguish the two types by the words "flat" and "round" or duplex (round) and twin (flat), until, in the course of years, the standards have become known.

Twin Cable.—A twin cable is a cable composed of two insulated stranded conductors laid parallel, having a common covering.

Twin Wire.—A twin wire is a cable composed of two small insulated conductors laid parallel, having a common covering.

Triplex Cable.—A triplex cable is a cable composed of three insulated single-conductor cables twisted together.

They may or may not have a common insulating covering.

Twisted Pair.—A twisted pair is a cable composed of two small insulated conductors, twisted together, without a common covering.

The two conductors of a "twisted pair" are usually substantially insulated, so that the combination is a special case of a "cord."

Sector Cable.—A sector cable is a multiple-conductor cable in which the cross-section of each conductor is substantially a sector, an ellipse or a figure intermediate between them.

Sector cables are used in order to obtain decreased overall diameter and thus permit the use of larger conductors in a cable of given diameter.

Round Conductor.—A round conductor is either a solid or stranded conductor of which the cross-section is substantially circular.

Split Conductor.—A split conductor is a conductor which is divided into two or more parts, separated from one another by insulation, which is thin compared with the insulation around the conductor.

The term "split conductor" usually designates a conductor in two parts or splits, which may be either concentric or external to one another.

Factor of Assurance.—The factor of assurance of wire or cable insulation is the ratio of the voltage at which it is tested to that at which it is used.

Insulation Resistance.—The insulation resistance of an insulated conductor is the electrical resistance offered by its insulation to an impressed voltage tending to produce a leakage of current through the same.

Circular Mil.—A circular mil is a unit of area equal to $\frac{\pi}{4}$ ($= 0.7854 \ldots$) of a square mil. The cross-sectional area of a circle in circular mils is therefore equal to the square of its diameter in mils. A circular inch is equal to a million circular mils.

A mil is the one-thousandth part of an inch. There are 1,974 cir. mils in a square millimeter.

Direction of Lay.—The direction of lay is the lateral direction in which the strands of a cable run over the top of the cable as they recede from an observer looking along the axis of the cable.

APPENDIX II

AMERICAN WIRE GAGE

In the United States, practically the only gage now used for copper wire is the American, or Brown and Sharpe, wire gage. Sizes of stranded conductors larger than No. 0000 A. w. g. are specified by the total cross-section in circular mils. It is becoming more and more the practice of the large electrical companies and others to omit gage numbers; and the stock sizes of copper wire used and specified by those who follow this practice are generally the American wire gage sizes, to the nearest mil for the larger diameters and to a tenth of a mil for the smaller.

The American wire gage, in common with a number of other gages, represents by its sizes approximately the successive steps in the process of wire drawing. Also, like many other gages, its numbers are retrogressive, a larger number denoting a smaller wire, corresponding to the operations of drawing.

The gage is formed by the specification of two diameters and the law that a given number of intermediate diameters are formed by geometrical progression. Thus, the diameter of No. 0000 is defined as 0.4600 in. and of No. 36 as 0.0050 in. There are 38 sizes between these two, hence the ratio of any diameter to the diameter of the next greatest number $= \sqrt[39]{\dfrac{0.4600}{0.0050}} = \sqrt[39]{92} = 1.122\,932\,2$. The square of this ratio $= 1.2610$. The sixth power of the ratio, *i.e.*, the ratio of any diameter to the diameter of the sixth greater number $= 2.0050$. The fact that this ratio is so nearly 2 is the basis of numerous useful approximate relations, such as that shown in the table below.

The law of geometrical progression on which the gage is based may be expressed in either of the three following manners: (1) the ratio of any diameter to the next smaller is a constant number; (2) the difference between any two successive diameters is a constant per cent of the smaller of the two diameters; (3) the difference between any two successive diameters is a constant ratio times the next smaller difference between two successive diameters.

Gage No.	Ohms per 1,000 ft.			Gage No.	Ohms per 1,000 ft.			Gage No.	Ohms per 1,000 ft.			Gage No.	Ohms per 1,000 ft.		
0	0.1	.....	....	10	1	....	...	20	10	....	..	30	100	...	...
1	...	0.125	....	11	..	1.25	...	21	..	12.5	..	31	...	125	...
2	...	.....	0.16	12	..	....	1.6	22	..	..	16	32	...	...	160
3	0.2	.....	....	13	2	....	...	23	20	..	..	33	200	...	...
4	...	0.25	....	14	..	2.5	...	24	..	25.0	..	34	...	250	...
5	...	.....	0.32	15	..	....	3.2	25	..	....	32	35	...	...	320
6	0.4	.....	....	16	4	....	...	26	40	....	..	36	400	...	...
7	...	0.5	....	17	..	5.0	...	27	..	50.0	..	37	...	500	...
8	...	.....	0.64	18	..	....	6.4	28	..	....	64	38	...	...	640
9	0.8	.....	....	19	8	....	...	29	80	....	..	39	800	...	...

The American wire gage suffers from the defect of being based upon a ratio which cannot be expressed in any other way than as an incommensurate fraction. It is nearly equal to the ratio $\sqrt[20]{10} = 1.1220$, used in Europe for the base of the "preferred number" series which is being employed in ratings and dimensional work on a large and increasing scale. Hence it is necessary in practice to limit the number of decimal points in which a gage diameter is to be used, the usual limit being the fourth significant figure except that the American Society for Testing Materials express wire sizes to the nearest mil only.

APPENDIX III

RESISTIVITY

The electrical resistivity of copper is the resistance of a piece of copper of unit dimensions. The mass resistivity is the resistance of a wire of unit length and unit weight. The resistivity proper, sometimes called the volume resistivity is the resistance of a wire of unit length and unit cross-sectional area. Resistivities are usually given for a temperature of 20° C.

Mass Resistivity.—The mass resistivity is used in the following formula:

$$R = \frac{l^2 d}{m} \quad \text{or } d = \frac{Rm}{l^2}$$

where R = resistance in ohms at 20° C.
l = length.
m = mass.
d = mass resistivity, which is the product of the resistance per unit length and the mass per unit length.

According to the units in which l and m are expressed, d has the following values:

Unit for l	Unit for m	d
Meter	Gram	0.15328
Mile	Pound	875.20

Resistivity or Volume Resistivity.—The (volume) resistivity is used in the following formula:

$$R = \frac{lr}{s} \quad \text{or } r = \frac{Rs}{l}$$

where R = resistance in ohms at 20° C.
l = length.
s = cross-sectional area.
r = volume resistivity.

According to the units in which l and m are expressed, r has the following values:

Unit for l	Unit for s	r
Meter	Square millimeter	0.017241
Foot	Circular Mil	10.371

Effect of Temperature.—The resistance of a copper wire measured between two points rigidly fixed to the wire increases with increase of temperature for two reasons: First, the length of a wire increases in greater proportion than its cross-sectional area, and, second, the mass resistivity of the metal itself increases.

The change of *resistance* per degree must be distinguished from the change of *resistivity* per degree. The former depends upon the resistivity and

temperature of reference; the latter is a constant independent of the resistivity and temperature of reference.

Temperature Coefficient of Resistance.

Let R_T = resistance of wire at $T°$ C.

a_T = temperature coefficient for $T°$ C.

Then if

R_t = resistance of wire at $t°$ C.

$$R_t = R_T[l + a_T(t - T)].$$

The temperature coefficients of *resistance* are given in the following table:

TEMPERATURE COEFFICIENTS OF COPPER FOR DIFFERENT INITIAL TEMPERATURES (CENTIGRADE) AND DIFFERENT CONDUCTIVITIES

Per cent conductivity	α_0	α_{15}	α_{20}	α_{25}	α_{30}	α_{50}
95	0.004 03	0.003 80	0.003 73	0.003 67	0.003 60	0.003 36
96	0.004 08	0.003 85	0.003 77	0.003 70	0.003 64	0.003 39
97	0.004 13	0.003 89	0.003 81	0.003 74	0.003 67	0.003 42
97.3	0.004 14	0.003 90	0.003 82	0.003 75	0.003 68	0.003 43
98	0.004 17	0.003 93	0.003 85	0.003 78	0.003 71	0.003 45
99	0.004 22	0.003 97	0.003 89	0.003 82	0.003 74	0.003 48
100	0.004 27	0.004 01	0.003 93	0.003 85	0.003 78	0.003 52
101	0.004 31	0.004 05	0.003 97	0.003 89	0.003 82	0.003 55

The table was calculated by means of the following formula, which holds for any per cent conductivity, n, within commercial ranges, and for Centigrade temperatures. (n is considered to be expressed decimally: *e.g.*, if per cent conductivity = 99 per cent, n = 0.99.)

$$\alpha_{t_1} = \frac{1}{\dfrac{1}{n(0.00393)} + (t_1 - 20)}.$$

Temperature Coefficient of Resistivity.

Let r_T = resistivity of a wire at $T°$ C.

r_t = resistivity of a wire at $t°$ C.

C = temperature coefficient of resistivity per degree.

$r_t = r_T + C(t - T)$.

The temperature coefficient of resistivity per degree Centigrade is as follows, expressed in different units:

0.000597 ohm per meter, gram.
0.0000681 ohm per meter, square millimeter.
0.00681 microhm centimeter, square centimeter.
3.41 ohms per mile, pound.
0.0409 ohm per foot, circular mil.

Resistance of a Wire at $t°$ C. When Its Dimensions at 20° C. Are Known (100 per cent conductivity at 20° C.).

Let R_t = resistance ohms at $t°$ C.
L = length in feet at 20° C.
S = circular mils cross-section at 20° C.

$$R_t = 10.371\,\frac{L}{S}[1 + 0.00393(t - 20)].$$

Resistance of a Wire at $t°$ C. When Its Dimensions at $t°$ C. Are Known (100 per cent conductivity at 20° C.).

Let R_t = resistance, ohms at $t°$ C.
L = length in feet at $t°$ C.
S = circular mils cross-section at 20° C.

$$R_t = 10.371\,\frac{L}{S}\,[1 + 0.003944(t - 20)]\,\left(\text{where } 0.003944 = \frac{0.0409}{10.371}\right).$$

Resistance of Stranded Conductors.—The cross-sectional area of a cable is considered to be the sum of the cross-sectional areas of its component wires, when measured perpendicular to their axes. Hence the current path is longer than in a solid wire of the same cross-sectional area. To allow for this, the A.I.E.E. Standardization Rules state that cables shall be assumed to have 2 per cent greater resistance than their equivalent solid wires. The table in Appendix IV is based upon this assumption.

APPENDIX IV

COPPER CABLES, CONCENTRIC-LAY

Circular mils and A. w. g. or B.&S. gage; English units; 100 per cent conductivity; density 8.89 at 20° C.

Circular mils and A. w. g.	Resistance at 25° C. or 77° F.		Weight in pounds, bare		Standard stranding		
	Ohms per 1,000 ft.	Ohms per mile	Per 1,000 ft.	Per mile	Number of wires	Diameter of wires in mils	Outside diameter in mils
2,000,000	0.00539	0.0285	6,180	32,600	127	125.5	1,631
1,900,000	0.00568	0.0300	5,870	31,000	127	122.3	1,590
1,800,000	0.00599	0.0316	5,560	29,300	127	119.1	1,548
1,700,000	0.00634	0.0335	5,250	27,700	127	115.7	1,504
1,600,000	0.00674	0.0356	4,940	26,100	127	112.2	1,459
1,500,000	0.00719	0.0380	4,630	24,500	91	128.4	1,412
1,400,000	0.00770	0.0407	4,320	22,800	91	124.0	1,364
1,300,000	0.00830	0.0438	4,010	21,200	91	119.5	1,315
1,200,000	0.00899	0.0475	3,710	19,600	91	114.8	1,263
1,100,000	0.00981	0.0518	3,400	17,900	91	109.9	1,209
1,000,000	0.0108	0.0570	3,090	16,300	61	128.0	1,152
950,000	0.0114	0.0600	2,930	15,490	61	124.8	1,123
900,000	0.0120	0.0633	2,780	14,670	61	121.5	1,093
850,000	0.0127	0.0670	2,620	13,860	61	118.0	1,062
800,000	0.0135	0.0712	2,470	13,040	61	114.5	1,031
750,000	0.0144	0.0759	2,320	12,230	61	110.9	998
700,000	0.0154	0.0814	2,160	11,410	61	107.1	964
650,000	0.0166	0.0876	2,010	10,600	61	103.2	929
600,000	0.0180	0.0949	1,850	9,780	61	99.2	893
550,000	0.0196	0.1036	1,700	8,970	61	95.0	855
500,000	0.0216	0.1139	1,540	8,150	37	116.2	814
450,000	0.0240	0.1266	1,390	7,340	37	110.3	772
400,000	0.0270	0.1424	1,240	6,520	37	104.0	728
350,000	0.0308	0.1627	1,080	5,710	37	97.3	681
300,000	0.0360	0.1899	926	4,890	37	90.0	630
250,000	0.0431	0.228	772	4,080	37	82.2	575
0000	0.0509	0.269	653	3,450	19	105.5	528
000	0.0642	0.339	518	2,735	19	94.0	470
00	0.0811	0.428	411	2,170	19	83.7	418
0	0.102	0.540	326	1,720	19	74.5	373
1	0.129	0.681	258	1,364	19	66.4	332
2	0.162	0.858	205	1,082	7	97.4	292
3	0.205	1.082	163	858	7	86.7	260
4	0.259	1.365	129	680	7	77.2	232
5	0.326	1.721	102	540	7	68.8	206
6	0.410	2.170	81.0	428	7	61.2	184
7	0.519	2.74	64.3	339	7	54.5	164
8	0.654	3.45	51.0	269	7	48.6	146

Note 1.—The table is based on the international standard of resistance of copper, which takes the fundamental mass resistivity = 0.15328 ohm (meter, gram) at 20° C., the corresponding temperature coefficient = 0.00393 at 20° C., and the density = 8.89 g. per cubic centimeter at 20° C. The temperature coefficient is proportional to the conductivity, whence the change of mass resistivity per degree Centigrade is a constant, 0.000597 ohm (meter, gram).

Note 2.—The values given in the table are only for annealed copper of the standard resistivity. The user of the table must apply the proper correction for copper of any other resistivity. Hard-drawn copper may be taken as about 2.7 per cent higher resistivity than annealed copper.

Note 3.—Ohms per mile, or pounds per mile, may be obtained by multiplying the respective values above by 5.28.

Note 4.—For complete tables and other data, see Circular No. 31 of the Bureau of Standards.

Resistance of Wires and Cables

(Based on the standards of the A.I.E.E.)

Resistance, ohms, of wire or cable which is 1,000 ft. long at 20° C.

(Stranded except for sizes smaller than No. 6 A. w. g.)

Size, A. w. g. or circular inches	20° C. 68° F.	25° C. 77° F.	30° C. 86° F.	35° C. 95° F.	40° C. 104° F.	45° C. 113° F.	50° C. 122° F.
14	2.525	2.574	2.624	2.674	2.723	2.773	2.822
12	1.588	1.619	1.650	1.682	1.713	1.744	1.775
10	0.9989	1.018	1.038	1.058	1.077	1.097	1.116
8	0.6282	0.6404	0.6527	0.6651	0.6774	0.6898	0.7021
6	0.403	0.410	0.419	0.427	0.435	0.442	0.450
4	0.253	0.259	0.263	0.268	0.273	0.278	0.283
2	0.159	0.162	0.166	0.169	0.172	0.175	0.178
1	0.126	0.129	0.131	0.134	0.136	0.139	0.141
0	0.100	0.102	0.104	0.106	0.108	0.110	0.112
00	0.0795	0.0811	0.0826	0.0842	0.0857	0.0873	0.0888
000	0.0630	0.0642	0.0655	0.0667	0.0680	0.0692	0.0705
0000	0.0500	0.0509	0.0519	0.0529	0.0539	0.0549	0.0559
Circular inches							
0.25	0.0423	0.0431	0.0440	0.0448	0.0456	0.0465	0.0473
0.35	0.0302	0.0308	0.0314	0.0320	0.0326	0.0332	0.0338
0.50	0.0211	0.0216	0.0220	0.0224	0.0228	0.0232	0.0236
0.75	0.0141	0.0144	0.0147	0.0149	0.0152	0.0155	0.0158
1.00	0.0106	0.0108	0.0110	0.0112	0.0114	0.0116	0.0118
1.25	0.00846	0.00863	0.00879	0.00896	0.00913	0.00929	0.00946
1.50	0.00705	0.00719	0.00733	0.00747	0.00760	0.00774	0.00788
1.75	0.00604	0.00616	0.00628	0.00640	0.00652	0.00664	0.00676
2.00	0.00529	0.00539	0.00550	0.00560	0.00570	0.00580	0.00591

Size, A. w. g. or circular inches	55° C. 131° F.	60° C. 140° F.	65° C. 149° F.	70° C. 158° F.	75° C. 167° F.	80° C. 176° F.	85° C. 185° F.
14	2.872	2.922	2.971	3.021	3.071	3.120	3.170
12	1.806	1.838	1.869	1.900	1.931	1.962	1.994
10	1.136	1.156	1.175	1.195	1.215	1.234	1.254
8	0.7144	0.7268	0.7391	0.7515	0.7638	0.7762	0.7885
6	0.458	0.466	0.474	0.482	0.490	0.498	0.506
4	0.288	0.293	0.298	0.303	0.308	0.313	0.318
2	0.181	0.184	0.188	0.191	0.194	0.197	0.200
1	0.144	0.146	0.149	0.151	0.154	0.156	0.158
0	0.114	0.116	0.118	0.120	0.122	0.124	0.126
00	0.0904	0.0920	0.0935	0.0951	0.0967	0.0982	0.0998
000	0.0717	0.0729	0.0742	0.0754	0.0767	0.0779	0.0791
0000	0.0569	0.0578	0.0588	0.0598	0.0608	0.0618	0.0628
Circular inches							
0.25	0.0481	0.0490	0.0498	0.0505	0.0514	0.0523	0.0531
0.35	0.0344	0.0350	0.0356	0.0362	0.0377	0.0378	0.0379
0.50	0.0241	0.0245	0.0249	0.0253	0.0257	0.0261	0.0266
0.75	0.0160	0.0163	0.0166	0.0169	0.0171	0.0174	0.0177
1.00	0.0120	0.0122	0.0125	0.0127	0.0129	0.0131	0.0133
1.25	0.00962	0.00979	0.00996	0.0101	0.0103	0.0105	0.0106
1.50	0.00802	0.00816	0.00830	0.00844	0.00857	0.00871	0.00885
1.75	0.00687	0.00699	0.00711	0.00723	0.00735	0.00747	0.00759
2.00	0.00602	0.00612	0.00622	0.00633	0.00643	0.00654	0.00664

APPENDIX V

THERMOMETER SCALES, COMPARISON OF

Fahrenheit	Centigrade	Fahrenheit	Centigrade	Fahrenheit	Centigrade
0	−17.7	35.6	2	70	21.1
1.4	−17	36	2.2	71	21.6
2	−16.6	37	2.7	71.6	22
3	−16.1	37.4	3	72	22.2
3.2	−16	38	3.3	73	22.7
4	−15.5	39	3.8	73.4	23
5	−15	39.2	4	74	23.3
6	−14.4	40	4.4	75	23.8
6.8	−14	41	5	75.2	24
7	−13.8	42	5.5	76	24.4
8	−13.3	42.8	6	77	25
8.6	−13	43	6.1	78	25.5
9	−12.7	44	6.6	78.8	26
10	−12.2	44.6	7	79	26.1
10.4	−12	45	7.2	80	26.6
11	−11.6	46	7.7	80.6	27
12	−11.1	46.4	8	81	27.2
12.2	−11	47	8.3	82	27.7
13	−10.5	48	8.8	82.4	28
14	−10	48.2	9	83	28.3
15	− 9.5	49	9.4	84	28.8
15.8	− 9	50	10	84.2	29
16	− 8.8	51	10.5	85	29.4
17	− 8.3	51.8	11	86	30
17.6	− 8	52	11.1	87	30.5
18	− 7.7	53	11.6	87.8	31
19	− 7.2	53.6	12	88	31.1
19.4	− 7	54	12.2	89	31.6
20	− 6.6	55	12.7	89.6	32
21	− 6.1	55.4	13	90	32.2
21.2	− 6	56	13.3	91	32.7
22	− 5.5	57	13.8	91.4	33
23	− 5	57.2	14	92	33.3
24	− 4.4	58	14.4	93	33.8
24.8	− 4	59	15	93.2	34
25	− 3.8	60	15.5	94	34.4
26	− 3.3	60.8	16	95	35
26.6	− 3	61	16.1	96	35.5
27	− 2.7	62	16.6	96.8	36
28	− 2.2	62.6	17	97	36.1
28.4	− 2	63	17.2	98	36.6
29	− 1.6	64	17.7	98.6	37
30	− 1.1	64.4	18	99	37.2
30.2	− 1	65	18.3	100	37.7
31	− 0.5	66	18.8	100.4	38
32	0.0	66.2	19	101	38.3
33	0.5	67	19.4	102	38.8
33.8	1	68	20	102.2	39
34	1.1	69	20.5	103	39.4
35	1.6	69.8	21	104	40

Fahrenheit	Centigrade	Fahrenheit	Centigrade	Fahrenheit	Centigrade
105	40.5	143	61.6	181	82.7
105.8	41	143.6	62	181.4	83
106	41.1	144	62.2	182	83.3
107	41.6	145	62.7	183	83.8
107.6	42	145.4	63	183.2	84
108	42.2	146	63.3	184	84.4
109	42.7	147	63.8	185	85
109.4	43	147.2	64	186	85.5
110	43.3	148	64.4	186.8	86
111	43.8	149	65	187	86.1
111.2	44	150	65.5	188	86.6
112	44.4	150.8	66	188.6	87
113	45	151	66.1	189	87.2
114	45.5	152	66.6	190	87.7
114.8	46	152.6	67	190.4	88
115	46.1	153	67.2	191	88.3
116	46.6	154	67.7	192	88.8
116.6	47	154.4	68	192.2	89
117	47.2	155	68.3	193	89.4
118	47.7	156	68.8	194	90
118.4	48	156.2	69	195	90.5
119	48.3	157	69.4	195.8	91
120	48.8	158	70	196	91.1
120.2	49	159	70.5	197	91.6
121	49.4	159.8	71	197.6	92
122	50	160	71.1	198	92.2
123	50.5	161	71.6	199	92.7
123.8	51	161.6	72	199.4	93
124	51.1	162	72.2	200	93.3
125	51.6	163	72.7	201	93.8
125.6	52	163.4	73	201.2	94
126	52.2	164	73.3	202	94.4
127	52.7	165	73.8	203	95
127.4	53	165.2	74	204	95.5
128	53.3	166	74.4	204.8	96
129	53.8	167	75	205	96.1
129.2	54	168	75.5	206	96.6
130	54.4	168.8	76	206.6	97
131	55	169	76.1	207	97.2
132	55.5	170	76.6	208	97.7
132.8	56	170.6	77	208.4	98
133	56.1	171	77.2	209	98.3
134	56.6	172	77.7	210	98.8
134.6	57	172.4	78	210.2	99
135	57.2	173	78.3	211	99.4
136	57.7	174	78.8	212	100
136.4	58	174.2	79		
137	58.3	175	79.4		
138	58.8	176	80		
138.2	59	177	80.5		
139	59.4	177.8	81		
140	60	178	81.1		
141	60.5	179	81.6		
141.8	61	179.6	82		
142	61.1	180	82.2		

APPENDIX VI

SIXTY-FOURTHS OF AN INCH IN MILLIMETERS

Sixty-fourths of an inch	Millimeters	Sixty-fourths of an inch	Millimeters
1	= 0.397	33	=13.097
2	= 0.794	34	=13.494
3	= 1.191	35	=13.891
4	= 1.588	36	=14.288
5	= 1.984	37	=14.684
6	= 2.381	38	=15.081
7	= 2.778	39	=15.478
8	= 3.175	40	=15.875
9	= 3.572	41	=16.272
10	= 3.969	42	=16.669
11	= 4.366	43	=17.066
12	= 4.763	44	=17.463
13	= 5.159	45	=17.859
14	= 5.556	46	=18.256
15	= 5.953	47	=18.653
16	= 6.350	48	=19.050
17	= 6.747	49	=19.447
18	= 7.144	50	=19.844
19	= 7.541	51	=20.241
20	= 7.938	52	=20.638
21	= 8.334	53	=21.034
22	= 8.731	54	=21.431
23	= 9.128	55	=21.828
24	= 9.525	56	=22.225
25	= 9.922	57	=22.622
26	=10.319	58	=23.019
27	=10.716	59	=23.416
28	=11.113	60	=23.813
29	=11.509	61	=24.209
30	=11.906	62	=24.606
31	=12.303	63	=25.003
32	=12.700	64	=25.400

APPENDIX VII

POWER FACTORS AND IMPERFECTION ANGLES

Power Factor, Per Cent	Imperfection Angle
0	0
0.1	0 deg. 4 min.
0.2	0 deg. 7 min.
0.3	0 deg. 10 min.
0.4	0 deg. 14 min.
0.5	0 deg. 17 min.
0.6	0 deg. 21 min.
0.7	0 deg. 24 min.
0.8	0 deg. 28 min.
0.9	0 deg. 31 min.
1.0	0 deg. 35 min.
1.5	0 deg. 52 min.
2.0	1 deg. 8 min.
2.5	1 deg. 26 min.
3.0	1 deg. 43 min.
3.5	2 deg. 1 min.
4.0	2 deg. 18 min.
4.5	2 deg. 35 min.
5.0	2 deg. 52 min.
10.0	5 deg. 45 min.
15.0	8 deg. 38 min.
20.0	11 deg. 33 min.
30.0	17 deg. 28 min.
40.0	23 deg. 35 min.
50.0	30 deg. 0 min.
75.0	48 deg. 36 min.
100.0	90 deg. 0 min.

APPENDIX VIII

SUMMARIZED HISTORY OF PUBLISHED KNOWLEDGE BEARING UPON THE PERFORMANCE OF INSULATION UNDER ELECTRIC STRESS

Prepared by the Subcommittee on Wires and Cables of the A.I.E.E. Standards Committee and brought up to date by C. F. Hanson and the author

GEOMETRIC RELATIONS WHICH AFFECT DIELECTRIC STRESS

Jona, E. (*Trans. Int. Elect. Cong.*, vol. 2, p. 550, 1904) showed that the electric stress in a dielectric between two concentric conducting cylinders, which is the simplest geometric representation of a single-conductor cable, follows the law.

$$H = \frac{E}{x \log_{\epsilon} \frac{R}{r}}$$

where

H = stress in kilovolts per centimeter at any point x cm. from the axis.
E = difference of potentials between cylinders, in kilovolts.
R = radius of outer cylinder, centimeters.
r = radius of inner cylinder, centimeters.

Levi, Civita (*Rendiconti Circolo Matematico di Palermo*, 1905, vol. 20, part 1, p. 173) gave formula for maximum stress including the effect of stranding.

Thornton, W. M. and Williams, O. J. (*Electrician*, 1909, vol. 63, p. 833) gave experimentally determined diagrams of electrostatic force both for round and sector triplex cables.

Deutsch, W. (*E.T.Z.*, 1911, vol. 32, p. 1175) derived approximate formula for the maximum stress including the effect of stranding.

Gorgas, Benischke, Petersen, Etc. (*E.T.Z.*, 1913, vol. 34, pp. 637, 783, 984, 1186, 1354) correspondence and discussion of stress at conductor surface, especially on approximate formula for stresses between parallel cylinders.

Middleton, W. I. and Dawes, C. L. (*Trans. A.I.E.E.*, 1914, vol. 33, p. 1185) discussed the logarithmic formula, and showed that the stress at the surface of a conductor was a minimum when $d = \frac{D}{2.72}$, where d is the diameter over the conductor, D is the diameter over the insulation and 2.72 is the Naperian logarithmic base e. There is also a discussion of overstressing of cables.

Russell, A. (*Proc. Phys. Soc. London*, 1919, vol. 33, p. 111) derives formula for stress between parallel cylinders.

ATKINSON, R. W. (*Trans. A.I.E.E.*, 1919, vol. 38–2, p. 971) developed a method of estimating the stresses in a triplex cable.

DEL MAR, W. A. (*Trans. A.I.E.E.*, 1919, vol. 38–2, p. 1018) gave diagrams of equipotential and stress lines in round and sector triplex cables.

DAVIS AND SIMONS (*Jour. A.I.E.E.*, p. 12, Jan., 1921) published tables of maximum stresses based on Atkinson's method.

EMANUELI, LUIGI (*L'Eletrotecnica*, 1921, vol. 8, p. 573) gave experimental determinations of stresses in three-conductor cables.

ELL, B. (*Elektrotech. Z.*, vol. 42, p. 1,194, Oct. 20, 1921, also *Science Abstracts*, sec. B., vol. 25, p. 103, Feb., 1922) describe a method of obtaining a photographic record of the distribution of the field in any given system of conductors and dielectrics. Photographs are given for a single-core and for a three-conductor cable with both direct and alternating current.

SCHWAIGER, A. (*Archiv. f. Elektrot.*, vol. 11, p. 41, Apr., 1922; *Science Abstracts*, vol. 25, p. 389, July, 1922) gave tables from which the author claims it is possible to make all breakdown calculations by simple multiplication, as in the case of plate electrodes.

SIMONS, D. M. (*Jour. A.I.E.E.*, vol. 41, p. 433, June, 1922) discussed the minimum-stress theory of cable breakdowns as developed by Fernie. He points out that the minimum stresses obtained by Fernie deviate from constancy about as much as the average stresses. The minimum stress at breakdown is not constant for all cables in general, but only for cables in which $\frac{R}{r}$ is greater than 2.72, and in this case the constancy can be explained in terms of the critical breakdown gradient of the insulation. More experimental data are needed.

MIDDLETON, W. I., DAWES, C. L. AND DAVIS, E. W. (*Jour. A.I.E.E.*, vol. 41, p. 572, Aug., 1922) obtained experimental evidence on the potential gradient in cables which indicates that for single-conductor cables:

1. Cables having values of $\frac{D}{d}$ equal to or less than 2.72 have a potential gradient which follows the simple logarithmic formula.

2. For values of $\frac{D}{d}$ greater than 2.72 the layers of insulation adjacent to the conductor can be subjected to stresses far in excess of those which the insulation can normally withstand and yet complete rupture does not occur.

3. Indications are that the insulation within the diameter $\frac{D}{2.72}$ adds nothing to the dielectric strength of the cable.

4. In calculating the maximum stress in three-conductor cables the wall of insulation should be assumed equal to the total insulation between conductors.

WISEMAN, R. J. (*Jour. A.I.E.E.*, p. 165, Feb., 1923), cited experiments on ceresine wax, showing that for this class of insulation the law for maximum stress is of the form

$$K = K_o\left(1 + \frac{a}{\sqrt{r}}\right)\sqrt{R}$$

where K is the constant in the formula, $E = Kr \log_\epsilon \frac{R}{r}$ and K_o and a are constants.

Peek, F. W. (*Jour. A.I.E.E.*, p. 965, Dec., 1922) suggested the following formula for the dielectric strength of single-conductor impregnated-paper cables:

$$K = 100\left(1 + \frac{1.1}{\sqrt{r}}\right) \text{ kv. per centimeter}$$

where K is as described in the previous abstract and r is the radius of the conductor in centimeters.

Atkinson, R. W. (*Jour. A.I.E.E.*, 1924) analyses the geometric factors of sector cables and derives curves showing the ratio of various stresses to the average stress, for various ratios of insulation thickness to conductor diameter.

DIELECTRIC FAILURE OF AIR

Steinmetz, C. P. (*Trans. A.I.E.E.*, 1893, vol. 15, p. 281) suggested that the diameter of a corona in air is such that the corona reduces the electric intensity (or potential gradient) at its boundary to the constant value of the electric strength of air.

Ryan, H. J. (*Trans. A.I.E.E.*, 1904, vol. 21, p. 275) found that the apparent dielectric strength of air around a wire varies with the diameter of the wire.

Jona, E. (*Trans. Int. Elect. Cong.*, 1904, vol. 2, p. 550) said that the diameter of the air corona, for a given arrangement of conductors, is independent of the size of wire and depends only on the voltage.

Townsend, J. S. (*Trans. Int. Elect. Cong., St. Louis*, 1904, vol. 1, p. 106) said that free ions exist in air and that they are accelerated in their motion when subjected to electric stress. When they attain a certain speed, they knock electrons from their atomic orbits, thus liberating the electrons and converting the atoms into ions.

Whitehead, J. B. (*Trans. A.I.E.E.*, 1910, vol. 29–2, p. 1183) said that, as the logarithmic law for concentric cylinders indicates different stresses at a given distance from the axis, with different conductor diameters and as corona observations indicate the same stress, the logarithmic law must fail when corona is present, and therefore the air carrying a corona must have a relatively high conductivity.

Hayden, J. R. and Steinmetz, C. P. (*Trans. A.I.E.E.*, 1910, vol. 29–2, p. 1125) showed that the disruptive discharge through a dielectric requires not merely a sufficiently high voltage, but also a definite minimum amount of energy.

Whitehead, J. B. (*Trans. A.I.E.E.*, 1910, vol. 29–2, p. 1159) said that an electron requires an intensity of 170 kv. per centimeter to give it sufficient velocity to break up a molecule by collision, and concluded from this that the ionizing agents, in the ionization by collision which creates corona, must be of atomic or molecular dimensions. Such ions require only 30 to 40 kv. per centimeter. He showed that there is no dielectric loss in air until the corona point is reached, that the electric strength of air is independent of the material of the electrode, that the corona voltage is lowered by surface impurities, that the corona has high conductivity and that most of the dielectric loss takes place beyond it.

Ryan, H. J. (*Trans. A.I.E.E.*, 1911, vol. 30–1, p. 1) applied the electron theory to the explanation of corona loss.

WHITEHEAD, J. B. (*Trans. A.I.E.E.*, 1911, vol. 30–3, pp. 1883–1885) gave evidence that corona is due to the liberation of ions from neutral molecules when the latter suffer collision with free ions moving under the impulse of an electric field.

PEEK, F. W. (*Trans. A.I.E.E.*, 1911, vol. 30–3, p. 1889) showed that the corona loss around a wire varies as the square of the excess voltage above the voltage at which corona starts. He also showed that the electric strength of air is about 30 kv. per centimeter and that corona starts when this intensity is attained at a distance of $0.301\sqrt{r}$ cm. from the surface of the conductor. This distance is called the energy distance. A finite thickness of air must be under a stress of 30 kv. per centimeter or more before breakdown occurs.

PEEK, F. W. (*Trans. A.I.E.E.*, 1912, vol. 31–1, p. 1051) showed that the energy distance for corona around cylindrical wires varies with the relative air density s and is

$$0.301\sqrt{\frac{r}{s}}\ \text{cm.}$$

PEEK, F. W. (*Trans. A.I.E.E.*, 1913, vol. 32–2, p. 1767) showed that the energy distance for spheres is

$$0.54\sqrt{\frac{r}{s}}$$

and that, where the electrodes are placed closer together than the energy distance, the apparent dielectric strength increases.

PEEK, F. W. (*Trans. A.I.E.E.*, 1915, vol. 34–2, p. 1857) showed that the time lag of breakdown is conveniently measured in microseconds, and that the lag varies with the electrode and is a maximum for the needle gap and a minimum for a uniform field or for a sphere gap.

WHITEHEAD, J. B. AND BROWN, W. S. (*Trans. A.I.E.E.*, 1917, vol. 36, p. 169) showed that corona appears at a lower value when the wire is positive than when negative, the maximum excess of negative over positive (which occurred for small diameters) being 6.3 per cent. The values for alternating current coincide with those for negative continuous voltage. Evidences in favor of Townsend's theory of ionization by collision are given.

PEEK, F. W. ("Dielectric Phenomena," p. 84) says that air between concentric cylindrical electrodes has its maximum electric strength when the diameter ratio is 3 instead of 2.72, the value to be expected if the logarithmic formula were strictly applicable. This he deduces from the energy distance and checks experimentally.

PEEK, F. W. ("Dielectric Phenomena," p. 85) says that the corona in air seems, in effect, to be either a series resistance or it grades or distributes the flux density when the conductor configuration is such that corona occurs before spark-over. He said that under this condition spark-over between concentric cylinders does not occur when $\frac{R}{r_1}$ = critical ratio, where r_1 = radius of corona, and R = radius of outer cylinder.

SCHUMANN, W. O. (*Archiv. f. Elektrot.*, vol. 11, p. 1, Apr., 1922; *Science Abstracts*, vol. 25, p. 384, July, 1922) shows that the electric strength of air depends upon the form and dimensions of the electrodes. The investigation will ultimately form the subject of a book.

Ryan, H. J. and Henline, H. H. (*Jour. A.I.E.E.* Sept. 1924, p. 825) showed that the power loss due to corona in air is a function of the peak voltages, as follows:

$$P = 4fc(E^2 - EE_o)$$

where

P = corona loss in watts per conductor
f = frequency
E_o = crest value of critical voltage to neutral
E = crest value of line voltage to neutral
C = capacitance (farads) of one conductor to neutral.

IONIZATION OF GAS IN SOLID INSULATION

Fessenden, R. F., in 1898 performed experiments which showed the danger of air bubbles in solid insulation.

Perrine, F. A. C. (*Trans. A.I.E.E.*, 1902, vol. 19, p. 1067) said that the failure of cable insulation is sometimes due to the presence of spaces filled with rarefied gases.

Petersen, W. (*Archiv. f. Elektrot.*, 1912, vol. 1, p. 28) called attention to the fact that air films in a dielectric of specific capacity K are subjected to a stress of K times that in the surrounding medium, and that ionization may, therefore, occur therein at comparatively low voltages. He also said that ions are shot from these films into the surrounding medium.

Dubsky, F. (*Trans. A.I.E.E.*, 1919, vol. 38–1, p. 537) measured the dielectric strength of thin air films between glass plates. He then applied these data theoretically to assumed gas spaces in solid dielectrics and showed the possible conditions under which ionization was likely to occur.

Shanklin, G. B. and Matson, J. J. (*Trans. A.I.E.E.*, 1919, vol. 38–1, p. 489) measured the ionization voltage in actual insulation designs by the dielectric-loss method. In the case of coil insulation, such as varnished-cambric and mica-paper, they give evidence showing that ionization not only occurs in the entrapped gas spaces but that it can cause serious damage. In the case of paper cables, evidence is given showing that a true ionization occurs. However, the exact nature of this ionization, its position and the possibilities of serious damage are not clearly shown.

Proos, C. F. (P. N. Van Kampen & Zoon, Sept., 1921; *Science Abstracts* vol. 25, p. 383, July, 1922) shows that the potential required to produce ionization in a cable depends upon the method used in manufacturing and the previous history of the cable, as, for example, the previous temperature of the cable. The a-c. conductance below the ionization point remains constant with increasing voltage, and above the ionization point it increases with increasing voltage until ionic saturation is reached, when again it becomes constant. Above the ionization point, the a-c. conductance depends upon the time of voltage application. The highest temperature reached in his experiments was 52° C. The dielectric loss was a minimum at about 35° C.

Hochstadter, M. (*Elektrotech. Z.*, 1922, vol. 43, pp. 575, 612, 641; *Science Abstracts*, vol. 25, p. 383, July, 1922) shows that the ionization phenomena and dielectric losses in high-tension cables depend, according to a well-defined law, on the temperatures at which measurements are made. The

total dielectric loss can be plotted on a V-shaped curve in relation to temperature, the minimum of which is at or near the temperature of solidification of the compound. He claims that air ionization does not entirely explain the increase of power factor with voltage.

Schrader, J. E. (*Jour. A.I.E.E.*, vol. 41, p. 702, Sept., 1922) gives results obtained with corona in air spaces in a dielectric. His data show the importance of excluding air spaces in a dielectric.

DIELECTRIC FAILURE OF TRANSFORMER OIL

Tobey, H. W. (*Trans. A.I.E.E.*, 1910, vol. 29, p. 1189), after discussing generally the testing of oils for dielectric strength, gives particulars of the influence of moisture on this property.

Hendricks, A. B. (*Trans. A.I.E.E.*, 1911, vol. 30–1, p. 167) showed that moisture has an important effect in reducing the dielectric strength of insulating materials. In the case of transformer oil, if E be the kilovolts producing breakdown between 0.5-in. disks, 0.2 in. apart, and x = parts of water in 10,000, by volume, then

$$E = \frac{19.2}{x^{0.284}}.$$

Hendricks, A. B. (*Trans. A.I.E.E.*, 1911, vol. 30–3, p. 1975) stated that transformer oil between concentric cylindrical electrodes has its maximum electric strength when the diameter ratio is about 7 instead of 2.72, the value to be expected if the logarithmic formula were applicable. He also said that the electric strength of transformer oil is increased by mechanical pressure, an increase from 0 to 200 lb. per square inch increasing the electric strength 50 per cent. This, by the electron theory, is due to the decreased mobility of the ions under pressure.

Peek, F. W. (*Gen. Elec. Rev.*, vol. 18, p. 821, Aug., 1915) states that a phenomenon similar to corona in gases also takes place in liquid insulations, such as oil, due to the tearing apart of the molecules of the oil or occluded gases. It seems that occluded gases often take an important part in supplying initial ionization. The effect of moisture is also pointed out.

Peek, F. W. (*Trans. A.I.E.E.*, 1915, vol. 34–2, p. 1857) found that the time lag is much greater for oil than for air.

Hirobe, T., Ogawa, W., and Kubo, S. (*Report, Electrochem. Lab., Tokyo, Japan,* 1916, report No. 25–3) showed that dust and fibrous matter in oil impair its insulating power, and that moisture has but little effect without absorbing media.

Peek, F. W. ("Dielectric Phenomena," 1920) showed that the dielectric strength of transformer oil can be increased by the use of baffles which confine the motion of the ions, impurities, etc.

Peek, F. W. ("Dielectric Phenomena," 1920) showed that transformer oil under electric stress exhibits properties similar to air. He showed that the energy distance is about $1.2\sqrt{r}$ cm., *i.e.*, about four times that of air, and that with such an energy distance, corona and spark-over voltages will be equal for ratios of $\frac{R}{r}$ up to at least 300.

Hayden, J. L. R. and Eddy, W. N. (*Jour. A.I.E.E.*, Feb., 1922) showed how the failure of transformer oil depends upon the presence of impurities. They

compared the number of failures at each voltage with the number to be expected according to the curve of probability, and found that they do not agree.

Friese, R. M. (*Elektrotech. Z.*, vol. 43, p. 54, Jan. 12, 1922; *Science Abstracts*, sec. B, vol. 25, p. 152, Mar., 1922) carried out experiments to determine the actual breakdown voltage of mineral oils, under varying conditions as regards the presence of moisture, other impurities, temperature and pressure. Small measured quantities of distilled water were added to carefully dried samples of oil and distributed throughout the oil by vigorous agitation. From the breakdown voltages obtained, it was found that the dielectric strength could be expressed by the formula:

$$D = \frac{1.1}{W} + 20.$$

D is in kilovolts per centimeter.

W is water in oil in parts per 1,000.

The maximum dielectric strength on dry oil was obtained between 60 and 70° C.

Hayden, J. L. R. and Eddy, W. N. (*Jour. A.I.E.E.*, vol. 41, p. 495, July, 1922) give results obtained from 3,000 tests on the dielectric strength of oil.

ELECTRIC PROPERTIES OF PETROLATUM

Malcles, L. (*Comp. rend.*, 1910, vol. 151, p. 63) furnished the idea that the behavior of petrolatum in an electric field is the result of free ions which are mobile when the petrolatum is fluid and immobile when it is jelly.

Del Mar, W. A. and Hanson, C. F. (*Jour. A.I.E.E.*, p. 439, June, 1922) give experimental data based upon ballistic galvanometer tests, which confirm Malcles' theory.

Hayden, J. L. R. and Eddy, W. N. (*Jour. A.I.E.E.*, p. 706, July, 1923) give data on the ratio of direct and peak alternating voltages which produce breakdown of petrolatum. They found this to be slightly below unity at temperatures from 25 to 100° C.

RESIDUAL CHARGE, POWER FACTOR AND ASSOCIATED EFFECTS

Faraday, M. ("Experimental Researches in Electricity," 1839) was probably the first to notice the phenomenon of residual charge.

Hopkinson, J. (*Phil. Trans.*, 1887, vol. 167, p. 599) showed that the residual charge is proportional to the exciting charge and gave results of experiments performed on several kinds of glasses, showing the effects of temperature. He noted that the residual charge in a Leyden jar can be promoted by tapping the dielectric, an indication that such charges are due to some internal polarization which is affected by shock.

Ayrton, W. E. and Perry, J. (*Proc. Roy. Soc., London*, 1878, vol. 27, p. 238) said that dielectrics exhibit an increase of strain under a prolonged constant dielectric stress and said that this was due to the "viscosity of the dielectric." They explained viscosity on the basis of the presence of comparatively conducting particles in "dielectrics of heterogeneous composition" and suggested that dielectrics and metals might owe their different properties to the presence of rotary molecular motion in the one and motion of translation in the other.

MAXWELL, J. C. ("A Treatise on Electricity and Magnetism," 1881, 2nd ed., vol. 1, chap. 10, p. 412) proved theoretically that a compound dielectric built up of layers of different non-absorptive dielectrics would exhibit both absorption and residual charge effects provided the product ρk is different for each lamina. (ρ = resistivity and k = specific capacity.)

MURAOKA, H. (*Wied. Ann.*, 1890, vol. 40, p. 329) found that, while paraffin and xylol showed practically no residual charge when separate, a layer of xylol on a layer of paraffin showed residual charge.

STEINMETZ, C. P. (*Elec. Eng.*, 1892, vol. 13, p. 272) showed that the energy consumed by a dielectric medium under alternating electrostatic strain is directly proportional to the square of the intensity of the electrostatic strain, or $H = kE^2$. Hence, whereas magnetic hysteresis follows the law of the 1.6 power, dielectric hysteresis follows the law of the square, that is, it acts just the same as a mere dead resistance connected into the circuit.

BEDELL, F. AND KINGSLEY, C. (*Phys. Rev.*, 1894, vol. 2, p. 170) showed, by the use of curves, the effects of a previous negative charge upon successive residual discharges, the effect of absorption upon the discharge curves, the effects of temperature on the resistance of oils and solid dielectrics.

STEINMETZ, C. P. (*Elec. World*, 1901, vol. 37, p. 1065) cited experiments on a paraffined paper condenser, showing that the dielectric loss is proportional to the square of the voltage and practically independent of the frequency. He suggested that the loss was largely due to mechanical motion of occluded air molecules under the influence of the alternating stress.

DRYSDALE, C. V. (*Electrician*, 1901, vol. 46, p. 890) gave data on dielectric loss in cables and condensers, and called attention to its importance due to the energy loss being a continuing one regardless of the load. He also gave tables of losses in dielectrics, power factors, etc., for different types of mica condensers with varying pressures.

TORCHIO, PHILIP (*Trans. A.E.I. Cos.*, 1902, pp. 217–219, quoted in *Trans. A.I.E.E.*, 1917, vol. 36, pp. 499–501) gave results of measurements of dielectric losses on long-feeder cables installed, and stated that "the dielectric losses are approximately proportional to the frequency, to the square of the voltage and to a certain function of the temperature not yet determined. The temperature, however, increases considerably the dielectric losses."

SKINNER, C. E. (*Trans. A.I.E.E.*, 1902, vol. 19, p. 1047) showed that dielectric loss varies with frequency, but not always in direct proportion. The variation from proportionality was especially marked at higher temperatures. He also showed that not only is the loss greater at high temperatures, but so is the rate of increase of loss.

PERRINE, F. A. C. (*Trans. A.I.E.E.*, 1902, vol. 19, p. 1067) said that work with cables has shown that a slight amount of moisture in the insulation will materially increase the heating, and that heating of this character almost invariably results in final breakdown.

MONASCH, B. (*Ann. Physik*, 1907, vol. 22, p. 905) said that the loss varies strictly as the square of the impressed voltage up to the point of formation of corona and that in cables at ordinary frequencies the loss is approximately proportional to the frequency.

FISHER, H. W. (*Trans. A.I.E.E.*, 1907, vol. 26–2, p. 997) gave data on the dielectric loss in rubber compounds and showed that compounds containing

a large amount of extractive matter may have lower losses than those containing small amounts.

TRAUTON, F. T. AND RUSS, S. (*Proc. Roy. Soc., London,* 1907, vol. 20, p. 551) showed experimentally that the recovered (residual) charge does not follow an exponential law as derived by Maxwell, but a logarithmic law.

SHUDDEMAGEN, C. L. B. (*Proc. Am. Acad. Arts Sci.,* 1909, vol. 44, p. 467) showed that the current which forms residual charge, or, in other words, the absorption current, is far from negligible when the charging interval is very small.

HOCHSTAEDTER, M. (*Elektrotech. Z.,* 1910, vol. 31, p. 467) reported that tests on impregnated-paper cables showed the dielectric loss to be exactly proportional to the frequency. He found that the maximum voltage in each cycle occurs simultaneously with the zero value of the current, but the maximum current does not coincide with zero voltage. He made a "dielectric hysteresis loop" from oscillograms and deduced therefrom the capacity, residual charge and dielectric loss.

DECOMBRE, L. (*Comp. rend.,* 1911, vol. 152, pp. 315, 1755) discusses dielectric loss in relation to polarization and makes some developments of Maxwell's theory. His reasoning, which is typical of that of several other physicists, is as follows:

The charge in a condenser is made up of two parts, one kE, due to an ether displacement and the other m, to a polarization of the dielectric, or $q = m + kE$. According to the theory of Lorentz,

$$a\frac{d^2m}{dt^2} + C\frac{dm}{dt} + bm = E$$

where a, b and c are positive coefficients. If the voltage E is alternating, the term $\frac{d^2m}{dt^2}$ which is proportional to f^2, where f is the frequency, is negligible, unless the frequency is of the order of that of light. Hence

$$c\frac{dm}{dt} + bm = E.$$

But the energy absorbed is Edq, *i.e.,* $E\ (dm + kdE)$. For a complete period the energy lost, if assumed to be dependent on the polarization of the dielectric, therefore equals

$$\int_0^T Edm \text{ or } \int_0^T C\left(\frac{dm}{dt}\right)^2 dt.$$

Hence, the alternate charge or discharge of a condenser causes a dissipation of energy proportional to the square of the polarization current, $\frac{dm}{dt}$.

RAYNER, E. H. (*Jour. I.E.E.,* 1912, vol. 49, p. 3) reported the results of an extended investigation to determine the relative effects of a short application of high-test voltage or longer application of lower test voltage. He also gave considerable information about the effect of humidity and temperature on the dielectric strength of insulating materials. The paper has a bibliography on the subject of dielectrics, containing 300 references, dated from 1864 to 1912.

Walker, Miles (*Jour. I.E.E.*, 1912, vol. 49, p. 71) showed that, if curves be made with temperature for abscissas and watts for ordinates, one curve giving the power lost in the cable and the other the power dissipated, an increase of temperature will be cumulative if the dissipation curve is above the loss curve, and non-cumulative if the reverse is true.

Fleming, J. A. and Dyke, G. B. (*Jour. I.E.E.*, 1912, vol. 49, p. 323) showed that two non-absorptive condensers of different capacities, each in series with a non-inductive resistance and the two connected in parallel, will act as a single condenser having absorption, if the products, c_1r_1 and c_2r_2 are unequal. This paper and the discussion thereon give a clear theoretical treatment of the subject and considerable experimental data to support the theory.

Addenbrooke, G. L. (*Electrician*, 1912, vol. 68, p. 829) showed by measurements at different frequencies that dielectrics may be considered to consist neither of capacities and resistances in series nor of capacities and resistances in parallel. He also showed that the loss in liquid dielectrics is independent of the frequency above a certain point, whereas in solids it increases with the frequency, but not always according to a linear law.

Pungs, L. (*Archiv. f. Elektrot.*, 1912, vol. 1, p. 329) showed that the dielectric losses in transformer oil are practically independent of the frequency. He concluded from this that the losses are due to ionic conduction rather than hysteresis. Resin oil showed similar properties, the loss increasing but slightly with the frequency.

Addenbrooke, G. L. (*Electrician*, 1913, vol. 70, p. 673) gives data on dielectric loss in gutta percha. He found the power factor to vary as follows with frequency.

Cycles	Power Factor, Per Cent
46	4.0
12	5.5
6	6.3
3	7.2
1.5	7.5

Wagner, K. W. (*Ann. phys.*, 1913, vol. 40, p. 817 and *Elektrotech. Z.*, 1913, vol. 34, p. 1,279) developed Maxwell's theory of residual charges arriving, like Maxwell, and unlike Trauton and Russ, at an exponential equation for residual charge current. He showed that his theory is consistent with observed facts regarding the relation between power factor and frequency. He also showed that his theory leads to the possibility of more than one maximum of dielectric loss at various temperatures, this also being in accordance with observed facts.

Evershed, S. (*Jour. I.E.E.*, 1914, vol. 52, p. 51) says that in absorbent insulators the conduction is not normally through continuous filaments of moisture but by endosmose. He explains endosmose as a motion of films of water along the walls of an insulator, due to the water being electropositive to practically all solid insulating materials and being, therefore, drawn through the pores of the solid toward its electronegative end, where a potential gradient is impressed on the solid. He explains the well-known time fall of insulation resistivity as being due to the spreading of moisture

globules over internal surfaces of the solid insulation under the influence of endosmose, *i.e.*, normally the moisture exists in globules separated by dry internal labyrinth surfaces of solid, but, when a potential gradient is applied, these globules spread over the surfaces of the labyrinth and reduce the resistance. When the potential gradient is removed, the films coalesce into globules, causing the resistivity to rise. Under the influence of an alternating-potential gradient, the globules do not have time to spread over the surfaces, but vibrate, causing a loss of energy. Evershed made a model insulator consisting of an inverted V-tube containing alternate drops of water and air, the ends of the tube being each set in a beaker. When a potential gradient was established between beakers, the drops of water spread along the walls of the glass tube, and the resistance characteristics were found to be similar to those of an absorbent insulator. When the potential gradient was raised, failure began in the form of sparking along the films from one drop to another.

Wagner, K. W. (*Elektrotech. Z.*, 1915, vol. 36, p. 111) developing Maxwell's theory of composite dielectrics shows by simple calculations that, in a dielectric composed of two elements, one of which was resistivity r and specific capacity k and the other resistivity R and specific capacity K, the residual charge will be zero if $rk = RK$. He also suggested that the dielectric loss would be zero under these conditions.

Skinner, C. E. (*Jour. Franklin Inst.*, 1917, vol. 183, p. 667) showed that the dielectric loss in transformer insulation follows the equation[1] $W = kE^n$, where the constants have the following values:

Temperature, degree Centigrade	k	n
30	0.025	2.34
40	0.032	2.27
50	0.044	2.22
60	0.068	2.21
70	0.107	2.18
80	0.155	2.15

Bang, A. F. and Louis, H. C. (*Trans. A.I.E.E.*, 1917, vol. 36, p. 431), following the method suggested by Walker, developed a method of determining the influence of dielectric losses on the rating of cables. They determined dielectric losses by the heating effects and gave data on the emissivity of conduit lines.

Clark, W. S. and Shanklin, G. B. (*Trans. A.I.E.E.*, 1917, vol. 36, p. 447) gave formulas for calculating dielectric loss in three-phase cables, data on dielectric losses, resistivities and specific capacities. They showed that when an impregnated-paper cable is bent, voids are created which become filled with gases from the volatilization of the oils (pp. 458–460). These reduce the resistivity at high voltages, due to the ionization of the gases. A comparison of losses in old and new cables is given.

[1] W = watts lost and E = effective kilovolts.

ATKINSON, R. W. (*Trans. A.I.E.E.*, 1917, vol. 36, p. 521) says that tests on impregnated-paper cables at 25 and 60 cycles showed that the loss at 25 cycles is always somewhat less than at 60 cycles, and in some cases is in almost direct ratio with the frequency. In other cases, there is little difference. Tests on a dried but unimpregnated-paper-lead cable showed the dielectric loss to be extremely low at all temperatures.

SWYNGEDAUW, R. (*Rev. gén. élec.*, vol. 5, p. 283, 1919) said that tests on triplex cables indicate that the dielectric loss obeys the following law:

$$W = (a + bE)fCE^2$$

where a and b are constants, C the capacity, f the frequency and E the voltage.

LUBBEN, C. (*Archiv. f. Elecktrot.*, vol. 10, p. 283, Dec., 1921 and *Science Abstracts*, sec. B, vol. 25, p. 244, Apr., 1922). From results obtained with a-c. tests on paper and in cables, the author gives curves showing: (1) the variation of capacity and dielectric-loss angle with frequency for high moisture contents, and (2) the increase in the losses as more moisture is absorbed. For large moisture contents the loss angle decreases with increasing frequency. The capacity and loss angle increase almost proportionally with increasing temperature.

The author also gives the relation between charging current and moisture content when d-c. voltage is applied.

HOCHSTADTER, M. (*Elektrotech. Z.*, vol. 43, p. 205, Feb., 1922; *Science Abstracts*, vol. 25, p. 245, Apr., 1922) discusses the subject of dielectric losses and limiting potential gradient in high-tension cables. He disagrees with Clark and Shanklin that the gradient should be limited to 19.5 kv. per centimeter. For carefully manufactured cables, he considers that 30 to 40 kv. per centimeter is permissible. He attributes limitations of the potential gradient to local homogeneities in the dielectric, due to manufacturing and handling or chemical changes due to combined influences of electrical stresses and temperature, which may give rise to local ionization and consequent hot spots.

ROPER, D. W. (*Jour. A.I.E.E.*, vol. 41, p. 423, June, 1922) shows from data obtained in the actual operation of cables that the majority of cable failures can be attributed to high dielectric loss because of the accompanying low critical temperature. By exercising greater care in the manufacture of cable and by keeping the dielectric loss low, the thickness of insulation can be materially reduced below that used in American practice at the present time.

DEL MAR, W. A. AND HANSON, C. F. (*Jour. A.I.E.E.*, vol. 41, p. 439, June, 1922) develop a theory, based upon the absorption theories of Maxwell and Wagner, explaining dielectric loss and substantiate it with data obtained on cables and flat samples of impregnated paper. They give results showing a relation between the resistivity of the impregnating compound and the power factor of the charging current flowing in the impregnated paper. A theory of dielectric strength is advanced, based on ionic motion in the oil and interference with this motion by the solid elements of the insulation.

DU BOIS, D. (*Jour. A.I.E.E.*, vol. 41, p. 689, Sept., 1922) gives the action and effect of moisture in a dielectric field from a mathematical point of view and verified by experiments. He found that a homogeneous dielectric of a

plastic nature, containing particles of moisture, would show absorption and residual charge and many other characteristics of actual insulation.

Steinmetz, C. P. (*Jour. A.I.E.E.*, 1923) gives a mathematical treatment of the Maxwell theory of absorption and its various consequences, both when direct and alternating current are used.

GRADING OF INSULATION

Jona, E. (1898) made graded cables and exhibited them at Milan.

O'Gorman, M. (*Jour. I.E.E.*, 1901, vol. 30, p. 608) showed that, to get uniform stress in a dielectric, the product Kx must be constant where K is specific capacity and x = radial distance from the axis of the cable.

Morris, J. P. (*Jour. I.E.E.*, 1907, vol. 40, p. 50) claims to have first suggested the use of intersheaths in the cable installation, in order to anchor the potential of the various layers of insulation in any manner desired by means of connections outside the cable.

Russell, A. (*Jour. I.E.E.*, 1907, vol. 40, p. 7 and *Electrician*, vol. 60, 1907, p. 160) said that when a dielectric under stress breaks down, a disruptive discharge ensues only when the effect of this partial breakdown is to increase the electric stress on the remaining portion. He also pointed out that in a composite dielectric subjected to alternating pressures, the voltages across the layers are usually out of phase with one another, and therefore that across each layer may be greater than indicated only by the thickness of the layer.

Osborne, H. (*Trans. A.I.E.E.*, 1910, vol. 29–2, p. 1553) gave revised formulas for the design of graded cables. He also advanced the theory that solid heterogeneous dielectrics fail due to corona in the elements of lower specific capacity. This corona is assumed to be in the form of needles.

Beaver, C. J. (*Jour. I.E.E.*, 1914, vol. 53, p. 57) mentions disadvantages of graded insulations and claims that desired results could be better obtained by means of intersheaths, because (1) there are no chemical interactions, (2) they are easier to joint, (3) there is no electrical discontinuity, (4) they could be tested layer by layer as manufactured, and (5) there is a much wider latitude in the choice of potentials.

Clark, W. S. and Shanklin, G. B. (*Trans. A.I.E.E.*, 1919, vol. 38–1, p. 923) say that practically no advantage is gained by an attempt to grade with rubber, varnished cambric and impregnated paper, because the maximum allowable working stresses in these materials vary inversely as their specific capacities. They claim that it is better to have the insulation a homogeneous compact mass of impregnated paper.

MISCELLANEOUS DATA

Rheins, G. (*Compt. rend.*, 1900, vol. 131, p. 505) says that the metal of cables penetrates the insulation and destroys its insulating properties. He said that, after 20 years, gutta-percha insulation will show copper in its outer layers, whereas with impregnated paper only a few layers were penetrated in four years. (No other experimenters report this phenomenon.)

O'Gorman, M. (*Jour. I.E.E.*, 1901, vol. 30, p. 608) called attention to the effect of putting in series two elements of insulation having different specific capacities. He showed that the potential gradient is altered, the material

of lower specific capacity carrying the greater part of the total potential drop across the two elements. (This fact seems to have been known to others at an earlier date.)

NEWBURY, F. J. (cited by PERRINE, *Trans. A.I.E.E.*, 1902, vol. 19, p. 1067) said that in his experiments with fiber cables he could increase the dielectric strength of the cable up to a certain point, by increasing the thickness of insulation; beyond that point the cable seems to break down at almost the same potential, irrespective of increase in thickness.

LANGSDORF, A. S. (*Elec. World*, 1908, vol. 52, p. 942) reported tests on various insulating materials at frequencies from 30 to 110, which seemed to indicate that if the applied e.m.f. is above a certain critical value, breakdown occurs after a definite number of repetitions of the electrostatic stress.

THORNTON, W. M. (*Phil. Mag.*, 1910, vol. 19, p. 390) showed that the electrical movement in a dielectric, when isolated in the field, is entirely confined to the molecule and is, therefore, neither metallic nor electrolytic in type, but is a continued displacement of the atomic charges to a greater degree of separation.

PETERSEN, W. (*Archiv. f. Elektrot.*, 1912, vol. 1, p. 28) showed that the refraction of lines of forces at the junction of two particles of different specific capacity in a dielectric may lead to an increase of dielectric stress.

HOLTTUM, W. (Abstracted from a report to *I.E.E.* in *Electrician*, 1913, vol. 71, p. 640) made tests on the relative dielectric strengths of ebonite for instantaneous and prolonged 50-cycle voltages and found that for stresses lasting a tenth of a second, the strength is only 25 per cent greater than for long-continued stresses.

LICHTENSTEIN, L. (*Elektrot. Z.*, 1917, vol. 33, p. 1179) says that the progress in the use of thin walls of insulation for high voltages is not due to a lower standard of safety in working, but to improved chemical, physical and mechanical processes of manufacture. He says that probably at very high test pressures an excess of 25 or 50 per cent over the working pressure ought to suffice.

BUTMAN, C. A. (*Elec. World*, 1918, vol. 71, p. 812) showed that the specific capacity of a heterogeneous combination, such as of fullerboards soaked in oil, separated by three layers of paraffin, may be greater than that of either component alone. Thus, combination = 4.25, fullerboard = 3.32, paraffin = 3.69.

FERNIE, F. (*Electrician*, 1919, p. 416, Oct. 10) pointed out the superior dielectric strength of oil around small, as compared with large, conductors.

ZELENY, J. (*Phys. Rev.*, 1920, vol. 16, p. 102) explained the added dielectric strength of an ionizable dielectric in contact with a small electrode as being due to the high-potential gradient at the surface of the electrode as compared with that a short distance away, the velocity of the ions consequently dropping below the value necessary for ionization by collision, when they have traveled a short distance from the electrode.

FERNIE, F. (*Beama*, p. 244, Sept., 1921) suggested that the stress which determines the failure of a cable is the minimum stress not the maximum.

FLIGHT, W. S. (*Jour. I.E.E.*, 1922 vol. 60, p. 218) gives data on the effect of heat on the electric strength of paper, micarta, varnished cloth and other materials. He showed that the electric strength of varnished cloth is about

42 per cent less at 100° C. than at 30° C., that of oil-saturated paper about 27 per cent less.

Zeleny, John (*Phys. Rev.*, vol. 19, p. 566, June, 1922) prepared sensitive points by grinding sewing needles to a fine point and then holding them an instant in an alcohol flame. The sensitiveness of points is determined by a compact layer of gas molecules, which offers a large resistance to the passage of ions but which may be penetrated and dissipated by ions with high speeds.

Wagner, C. W. (*Jour. A.I.E.E.*, p. 1,034, Dec., 1922) proved by experiments that a solid dielectric does not fail or break down because a critical potential gradient has been reached within certain parts of the dielectric. He showed that the failure occurs because of lack of homogeneity. In a local part of the insulation the electrical resistivity is low and therefore a greater current flows in this part than in neighboring parts. This increased current produces heat and the resistivity falls still lower because of the high negative temperature coefficient of resistivity. As the resistivity decreases the current increases, producing heat at a still greater rate. As the heat resistance is high, heating accumulates rapidly. The whole phenomenon may occur in a small fraction of a second. The dielectric first fails locally and the failure then spreads until a complete puncture occurs.

VOLTAGE RISES IN CABLES

Dwight, H. B. and Baker, C. W. (*Elec. Jour.*, 1911, vol. 8, p. 1102) showed that, when an iron-core inductance, such as a reactor or a transformer, is in series with a condenser, abnormal voltages may occur in the circuit, depending upon the saturation of the core and the capacity in the circuit. This is explained by a consideration of the volt-ampere characteristics of the inductance and the condenser. The former will be a curve concave toward the current axis; the latter will be a straight line which, in the case under consideration, cuts the curve. The total drop across the inductance and the condenser will be the difference of these two curves and will be represented by a wavy curve having zero voltage both at zero current and at the current where the two above curves intersect. The volt-ampere characteristic of the circuit resistance will also be a straight line, and the total circuit e.m.f. will be the quadrature resultant of the resistance drop and the total reactive drop. If such a curve be plotted, it will be found that there are two stable current values for a given voltage and the current obtained will depend on the point of the impressed e.m.f. wave at which the circuit is closed. In a case cited, voltages to ground of 3,800 and 6,000 were obtained, on a circuit where the applied three-phase voltage was 2,400. High-frequency harmonics were also found to be superimposed on the rise of fundamental frequency voltage described above.

Dwight, H. B. (*Elec. Jour.*, 1924, vol. 21, p. 324) elaborated his 1911 thesis, citing a case where insulators were being tested, a choke coil being in the primary (low-tension) of the testing transformer. On closing the primary (low-tension) circuit, the voltage on the primary was sometimes 30,000 and sometimes 300,000 volts (See also *Trans. A.I.E.E.*, 1914, p. 996).

A similar phenomenon occurred when an artificial neutral was made with potential transformers on a set of delta-connected transformers. On closing

the ground switch, a voltage was sometimes generated, sufficient to flash over the station insulators; at other times the voltage was quite normal.

In general, the author says that iron-cored reactors should be used with great caution where there is considerable capacity in the circuit.

Fleischmann, L. (*Gen. Elec. Rev.*, 1924, vol. 27, p. 260) gave a graphic treatment for the solution of circuit resonance problems where the inductance is variable, due to the presence of an iron core.

Taylor, A. M. (*Electrician*, 1924, vol. 93, p. 690) investigated the case of a transmission system in which the charging current exceeds the excitation current of the transformer, thus causing an abnormal voltage in the transformer secondary, by increasing the flux. If, after the high-tension line has been opened at its distant end, the low-tension circuit is suddenly opened, there is nothing to oppose the rise of flux in the transformer, except the saturation of the iron and the rapid increase of hysteresis loss therein.

Fallou, J. (*Rev. Gen. Elec.*, 1924, vol. 15, p. 468) tells of voltage rises on a three-phase transmission line consisting of three single-conductor cables and showed that these occurred as the result of opening the oil switches while the cables were taking charging current only. Under these conditions the voltage is a maximum while the current is ruptured at its zero point, thereby leaving the cable charged. The cable discharges across the oil-switch terminals and several cycles of high-frequency current pass, which result in a piling up of charges on the cable, which may raise the latter to triple normal potential.

Partridge, G. W. (*Elec. Rev.* 1924, vol. 94, p. 992) gave an account of voltage rises on a system having 10,500 volts to ground. The system consists partly of old cables having high dielectric loss, especially in the joints, and partly of modern cables, all connected together into one network. It was found that very serious rises in pressure take place when, under certain conditions, the current is broken by an oil-switch at points other than the zero point of the pressure wave. The rise in pressure which actually took place on the system, as measured by an oscillograph, amounted to about four times the working pressure although lasting only about one-one-hundredth part of a second. Troubles were eliminated by introducing between conductors and ground a number of non-arcing spark gaps, current limiting resistances and a protective fuse in series. Whenever the voltage rose above a predetermined value, an indicator paper was perforated. During 5 years, this apparatus operated on 332 occasions, indicating pressure rises of at least 35 per cent. The pressure rises on the 6½ miles of old cable were 52, while those on the 21½ miles of modern cable were 280, *i. e.* 60 per cent more per mile on the low loss cable. During the six summer months, the apparatus operated on 232 occasions, whereas during the 6 winter months it operated on 100 occasions. During the night shift, that is on light load, there was three times as many rises in pressure as in the other two shifts put together. The reason for the rises in pressure is in many cases quite obscure.

APPENDIX IX

Maximum Voltage Stress in Triplex Round-conductor Cables under Three-phase Voltage

To obtain the maximum stress for a given cable, find the number in the following table corresponding to the size of conductor and conductor insulation thickness. Multiply the voltage in kilovolts between conductors by this number, and the product will be the maximum stress in kilovolts per centimeter. (*Davis and Simons.*)

Size A. w. g. strand	Diameter, inches	Conductor insulation thickness in thirty-seconds of an inch													
		3	4	5	6	7	8	9	10	11	12	13	14	15	16
4	0.232	2.74	2.28	1.97	1.77	1.63	1.51	1.42	1.35	1.29	1.23	1.19	1.15	1.11	1.08
3	0.260	2.63	2.18	1.89	1.68	1.54	1.42	1.35	1.27	1.22	1.16	1.12	1.08	1.04	1.01
2	0.292	2.52	2.10	1.82	1.62	1.47	1.36	1.28	1.21	1.15	1.10	1.05	1.02	0.98	0.95
1	0.328	2.42	2.01	1.74	1.55	1.40	1.29	1.21	1.14	1.09	1.04	1.00	0.96	0.93	0.90
0	0.373	2.30	1.92	1.66	1.48	1.34	1.23	1.14	1.08	1.02	0.98	0.94	0.90	0.87	0.84
00	0.418	2.21	1.85	1.60	1.42	1.29	1.18	1.09	1.03	0.97	0.93	0.89	0.85	0.82	0.80
000	0.470	2.11	1.77	1.53	1.36	1.23	1.13	1.05	0.98	0.93	0.88	0.84	0.81	0.78	0.75
0000	0.528	2.02	1.69	1.47	1.31	1.18	1.08	1.01	0.94	0.89	0.84	0.80	0.77	0.74	0.71
250,000 CM	0.575	1.95	1.64	1.42	1.27	1.15	1.05	0.98	0.91	0.86	0.81	0.77	0.74	0.71	0.69
300,000	0.630	....	1.58	1.38	1.23	1.11	1.02	0.94	0.88	0.83	0.79	0.75	0.71	0.68	0.66
350,000	0.681	....	1.53	1.34	1.19	1.08	0.99	0.92	0.86	0.81	0.76	0.72	0.69	0.66	0.64
400,000	0.728	....	....	1.30	1.15	1.05	0.97	0.90	0.84	0.79	0.75	0.71	0.67	0.65	0.62
450,000	0.772	....	....	1.27	1.13	1.03	0.95	0.88	0.82	0.77	0.73	0.69	0.66	0.63	0.61
500,000	0.815	....	....	1.25	1.11	1.01	0.93	0.86	0.81	0.76	0.72	0.68	0.65	0.62	0.60
550,000	0.855	....	....	1.22	1.09	0.99	0.91	0.85	0.79	0.74	0.70	0.67	0.64	0.61	0.59
600,000	0.893	....	....	....	1.08	0.98	0.90	0.84	0.78	0.73	0.69	0.66	0.63	0.60	0.58
650,000	0.929	....	....	....	1.06	0.96	0.89	0.82	0.77	0.72	0.68	0.65	0.62	0.59	0.57
1,000,000	1.152	....	....	....	0.97	0.89	0.82	0.78	0.71	0.67	0.63	0.60	0.57	0.55	0.53

(In sector cables, the maximum stress may be at the outer corners, in which case it will be between conductor and sheath. The maximum stress between conductors in sector cables will usually be somewhat greater than in round-conductor cables, an average difference being 10 per cent. More accurate factors are given by R. W. Atkinson, *Trans. A.I.E.E.*, 1924.)

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